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PORPOISE PERFORMANCE TESTS IN A SEA-WATER TANK

by

Thomas G. Lang
and
Dorothy A. Daybell
Research Department

ABSTRACT. This report deals with a series of tests—consisting of measurements of top speed, horsepower output, and drag coefficient—made to determine how a porpoise's power compares with that of other mammals, and how its hydrodynamic characteristics compare with those of conventional man-made submerged bodies. Results of the tests indicated no unusual physiological or hydrodynamic phenomena; power values were comparable to human power levels. These results, however, are in conflict with observations of unusual sea-animal performance reported in the open literature. Because the tank used in the tests may have affected test results, it is recommended that further tests be conducted under open-ocean conditions and their results checked against the results arrived at in this report. The experimental methods and theoretical analyses used in this report will aid such future studies.

U.S. NAVAL ORDNANCE TEST STATION
China Lake, California
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FOREWORD

Studies of sea phenomena and of various sea animals are of considerable interest because they satisfy curiosities fundamental to all of us, mariner and lubber alike. This study, dealing with the hydrodynamics of the porpoise, has a more specific purpose in that it, and others like it, may in time lead to the development of techniques for reducing the drag of ships and other vessels, thus adding to the speed, economy, and safety of water travel and to greater effectiveness of the Fleet. This study, the few that have gone before, and those in progress are only the beginnings, and although the results are not conclusive a good deal has been learned and the door opened to a rich field of investigation in cetacean research.

This study began in March 1960 under the over-all direction of R. L. Engel and continued through August 1960. The study was funded primarily by NOTS Task Assignment No. 803-767/73004/08060, and secondarily by Task Assignment RUTO-3E-000/216-1/R009-01-003 and ONR Project Order 747, Amendment 1, dated 24 March 1960.

This report was reviewed for technical accuracy by R. L. Engel and J. Hoyt.

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NOMENCLATURE

a	Porpoise acceleration, ft/sec^2
C_D	Drag coefficient based on surface area of any specific part of the porpoise
C_{D^*}	Collar drag coefficient based on frontal area
C_{D_c}	Collar drag coefficient based on body surface area
C_{D_o}	Drag coefficient of a cylinder adjacent to a flat surface and placed perpendicular to the flow
C_{D_r}	Roughness drag coefficient based on wetted area
C_{D_w}	Frictional drag coefficient of porpoise body based on body surface area
C_f	Frictional drag coefficient based on surface area
C_r	Local drag coefficient based on surface area
d	Maximum diameter of body, ft
D	Drag, lb
D'	Drag area, D/q, ft^2
$(D/q)_a$	Drag area of the appendages, ft^2
$(D/q)_r$	Roughness drag area, ft^2
f	Collar tube diameter, ft
g	Gravitational acceleration, ft/sec^2
h	Maximum height of the center of gravity of the porpoise above water, ft
h_e	Height of the center of gravity above water when the tail emerges, ft
HP_a	Acceleration horsepower
HP_D	Drag horsepower
k_1	Longitudinal virtual-mass coefficient
ℓ	Body length, ft
m_L	Effective longitudinal mass, slugs
m_o	Mass of porpoise, slugs
P	Power at time, ft-lb/sec
q	Dynamic pressure, lb/ft^2
R_c	Reynolds number based on chord length of fin
R_e	Reynolds number at end of a fully turbulent boundary layer that begins at a distance, Δx, ahead of the transition point
R_ℓ	Reynolds number based on length
R_x	Reynolds number based on distance from the leading edge

$R_{\Delta x}$	Reynolds number in turbulent flow based on a hypothetical length, Δx, producing a momentum thickness, Θ_t
s	Distance traveled during acceleration, ft
S	Wetted surface area of any specific part of the porpoise, ft^2
$S_{\cdot}$	Collar frontal area, ft^2
S_w	Porpoise body, wetted area, ft^2
t	Time, sec
T	Thrust, lb
t'	Thickness-to-chord ratio of a hydrofoil or hydrofoil-shaped fin
t_a	Period of acceleration, sec
V	Porpoise velocity, ft/sec
$\dot{V}$	dV/dt, acceleration, ft/sec^2
V_e	Water-exit velocity when the tail emerges, ft/sec
X	Distance traveled, ft
$\dot{X}$	Porpoise velocity at distance X, ft/sec
X_Δ	Spacing between hoops, ft
z	Depth, ft
δ_ℓ	Thickness of the boundary layer immediately ahead of the collar, ft
δ_Δ	Displacement thickness of the boundary layer immediately ahead of the collar, ft
η	Propulsive efficiency
Θ_c	Additional momentum thickness produced by the collar, ft
Θ_ℓ	Momentum thickness in the laminar boundary layer immediately ahead of the transition point, ft
Θ_t	Momentum thickness in the turbulent boundary layer immediately behind the transition point, ft
ρ	Water density, $slugs/ft^3$
τ	Parameter used for integration, representing time, sec

INTRODUCTION

Observers aboard high-speed ocean craft claim that they have seen porpoises and whales travel as fast as 20 to 35 knots. An analysis of torpedoes and submarines, of the same size, shows that either the sea animals produce much greater power than expected or their drag is much lower than expected. References 1, 2, and 3 contain data on speed and power. These data are analyzed later in this report.

The purpose of the performance tests reported herein was to determine whether a porpoise is more powerful than other mammals and whether it has hydrodynamic characteristics superior to conventional, man-made submerged bodies. The tests consisted of measurements of top speed, horsepower output, and drag coefficient.

These performance tests were conducted in a towing tank at Convair Division of General Dynamics Corp., San Diego, California, as part of a group of porpoise studies. Other studies included flow visualization experiments, physiological studies, and sonar studies. These will be reported by others in separate Naval Ordnance Test Station (NOTS) reports.

TEST DESCRIPTION

TEST SITE

The performance tests were conducted in the towing tank at the Convair Hydrodynamics Laboratory. This tank is 315 feet long, 12 feet wide, and 6.5 feet deep. It was filled with sea water for the porpoise experiments. A gate was placed near one end of the tank to form a pen for the porpoise. Tests were conducted on 3, 4, and 5 June 1960, with a water depth of 4.5 feet, and on 15 June 1960, with a water depth of 6 feet.

PORPOISE

The porpoise (Fig. 1) used in this program was of the species *Lagenorhyncus obliquidens* (Pacific Whitesided Dolphin) and was caught off Catalina Island by Marineland of the Pacific, Palos Verdes, California. The porpoise was nicknamed Notty. Although the animal is technically a dolphin, it is commonly called a porpoise and will be so called in this report. Notty's measurements are shown in Fig. 2. Her effective weight while swimming was 215 pounds, which includes 15 pounds for the added weight of the water that she carried along. Her average food intake each day was 15 pounds of mackerel, which is considerably more than that of a human of equivalent weight.

NATURE OF TESTS

The tests were designed so that the performance results might be cross-checked to provide better insurance of success. The tests were composed of two types of run down the tank. One type was a peak-effort run and the other was a motionless glide.

FIG. 1. The Porpoise Notty.

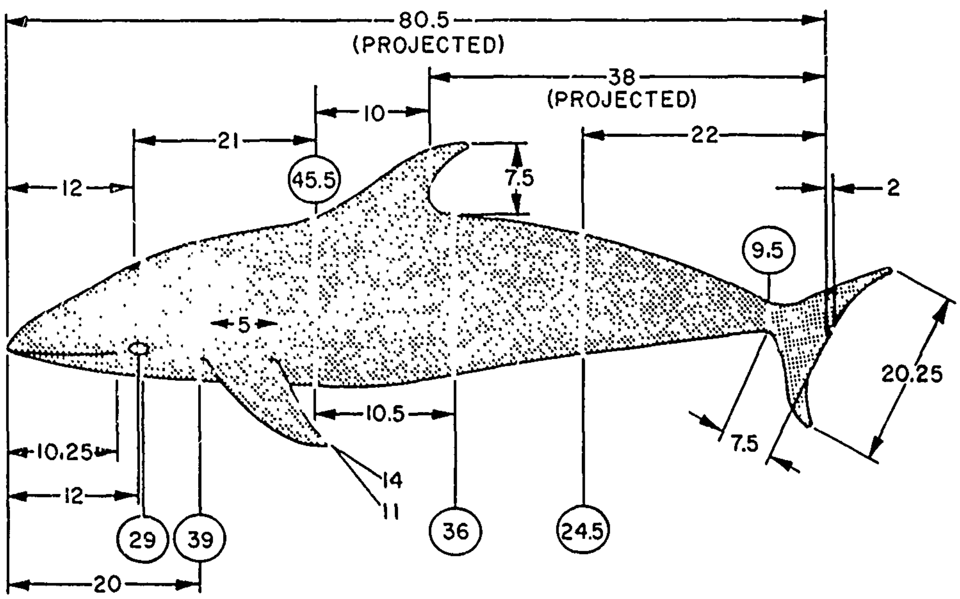


FIG. 2. Notty's Measurements (Inches). Circled numbers are girth measurements.

These two types of run were also made while the porpoise was wearing various collars. The thinnest collar, made of 1/16-inch coated wire, was used to induce turbulent flow. The thicker collars were used to add drag to the porpoise without appreciably interfering with its body movements, so that its power output could be measured at various top speeds.

The acceleration horsepower, with and without a collar, was calculated from the peak-effort runs. The drag coefficient was computed from the deceleration rates measured during the glide tests. Values of drag horsepower were then calculated using these experimental drag coefficients and the maximum velocities recorded. Approximate exertion times were obtained for these horsepower measurements, and comparisons were made with power measurements of humans.

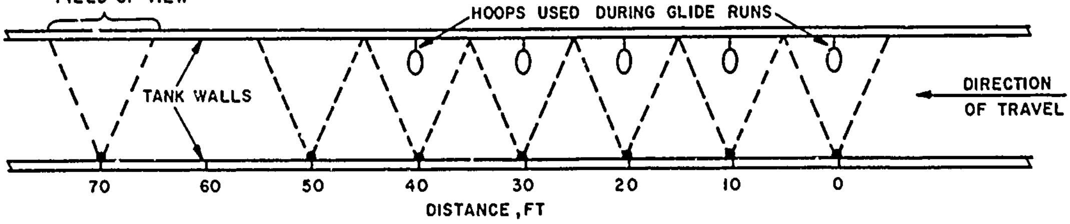
The state of the boundary layer was inferred from drag coefficients measured for the porpoise with no collar and with the 1/16-inch collar. The effective drag of the porpoise while swimming was compared with that while gliding by using an indirect method described in the analysis section.

TRAINING

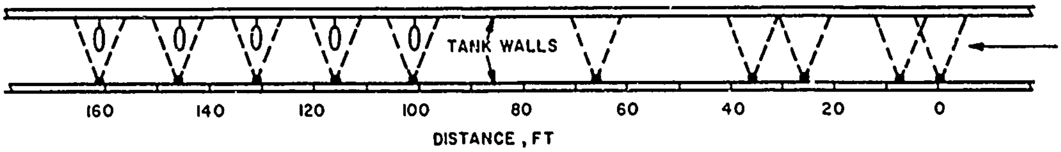
The training began by taming the porpoise and teaching it to accept prepared food. It was then taught to swim at peak effort in response to a hand signal. It was found during training that the porpoise tended to reduce body movement when passing through a series of large underwater hoops. Therefore, a series of hoops, spaced at 10- to 15-foot intervals at a centerline depth of about 2 feet, was used for the glide runs. Finally, Notty was taught to swim and glide while wearing the collars and even to "put them on" herself. A type of training called operant conditioning was used, which consists of rewarding the animal with food for conducting the desired task. In this way, the faster it swam the more chance it had of being immediately rewarded with food.

INSTRUMENTATION

The instrumentation consisted of 10 high-speed Mitchell cameras with a 100-pulse/sec binary-coded timing system, accurate to 0.001 second. The cameras were generally operated at 120 frames/sec. Most of the cameras were mounted above water and positioned as shown in Fig. 3.



(a)



(b)

FIG. 3. Camera and Hoop Locations. (a) Tests of 3, 4, 5 June; (b) 15 June tests.

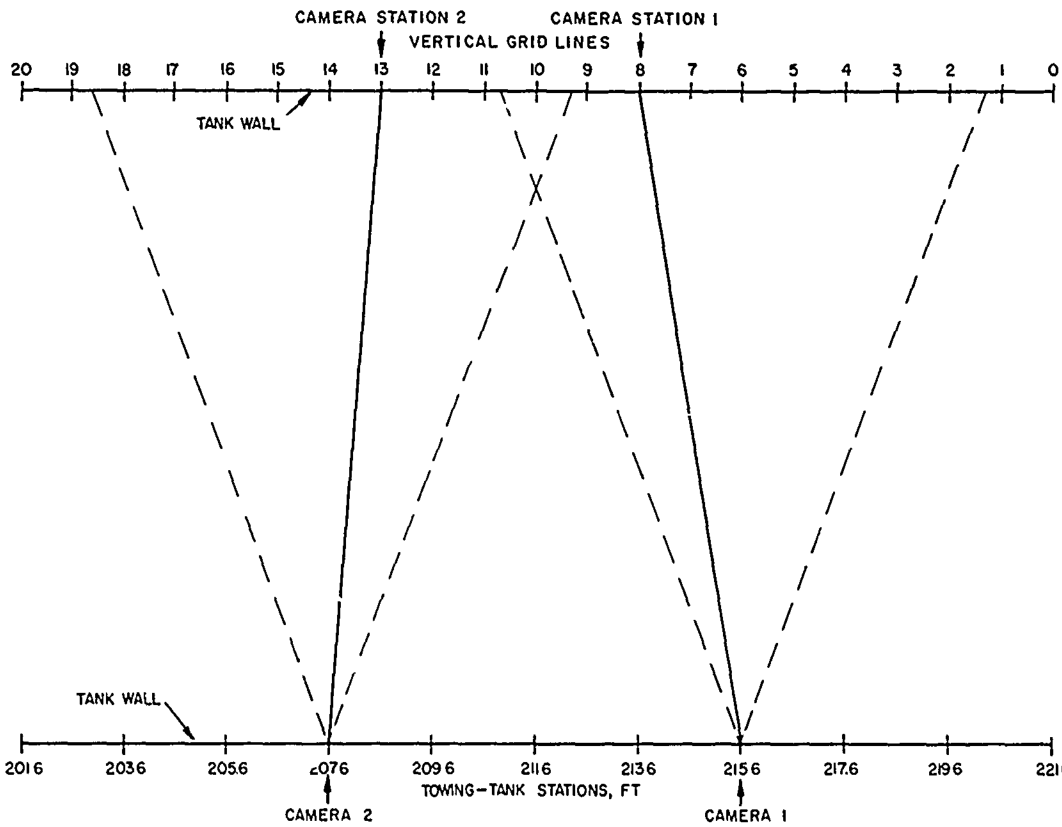


FIG. 4. Location of the Two Cameras Mounted at an Underwater Window; Plan View.

A vertical marker was placed underwater against the wall opposite each camera to provide a distance mark. The accuracy of the overhead cameras was reduced because of distortion caused by surface waves generated when the porpoise emerged for air. Velocities obtained were average values between camera stations and their accuracy was ±5%. For the 15 June tests, the first two cameras were mounted at an underwater window and faced a grid on the opposite wall (Fig. 4). The timing of camera number 2 on 15 June was later discovered to have malfunctioned on all but two runs, so some valuable acceleration data were lost.

PORPOISE CONFIGURATION

The configurations tested were of the bare porpoise and the porpoise with a collar around its "neck." The collars were placed 18 inches behind the "nose" and had an inner diameter of 10.5 inches and thicknesses of 1/16, 3/8, 1/2, 3/4, and 1 inch. The 1/16-inch collar was made of plastic-coated wire. The larger collars were made of hollow air-tight polyvinyl tubing (Tygon) and would float.

SALT-WATER CLARITY

The greatest problem encountered during the test program, and one that delayed the program considerably, was that of maintaining clear water. Partial success was obtained when salt water was brought by Navy tanker from outside San Diego Bay and pumped into the towing tank. This

water eventually became cloudy, even though chemicals were added. The tank was drained and refilled again for the 15 June tests, but this time some different chemicals were added, as recommended by Marineland. High filter rates and use of these chemicals kept the water acceptably clear. Unfortunately, leaks developed in the tanker's hose on the first filling, so the tank was only filled to a depth of 4.5 feet rather than the usual 6 feet.

THEORY

EQUATIONS OF MOTION

The longitudinal equation of motion is

$$T - D = m_L a$$

where

T = thrust, lb

$D = D'\rho V^2/2$ = drag, lb

m_L = effective longitudinal mass, slugs $= m_o(1 + k_1)$

m_o = mass of porpoise, slugs = 6.22

k_1 = longitudinal virtual-mass coefficient for ellipsoid of similar shape = 0.045

$m_L = 6.22(1 + 0.045) = 6.50$

a = porpoise acceleration, ft/sec^2

$D' = \dfrac{D}{\rho V^2/2}$ = drag area, ft^2

ρ = water density $\approx$ 2.0 slugs/ft^3

V = porpoise velocity, ft/sec

The horsepower required to accelerate a frictionless body is

$$HP_a = m_L aV/550$$

The horsepower required to propel a body with a known drag area, D', at speed V is

$$HP_D = \frac{D'\rho V^3/2}{550}$$

The total horsepower produced by the porpoise, including its propulsive efficiency, η, is

$$HP_{\text{produced}} = (HP_a + HP_D)/\eta$$

In general, it is believed η will lie between 0.70 and 0.95. The higher value of η would apply to constant-speed runs, and the lower value to the lower speeds with high acceleration. Values of η as high as 0.85 have been measured for torpedo propellers that make use of the boundary layer water.

GLIDE

When the porpoise is gliding without body movement, the equation of motion reduces to

$$-D'\rho V^2/2 = m_L a = m_L \dot{V}$$

Solving this differential equation,

$$D' = \frac{2m_L}{\rho}\left(\frac{1/V_2 - 1/V_1}{t_2 - t_1}\right)$$

where

V_1 = velocity at beginning of glide, when time = t_1

V_2 = velocity at end of glide, when time = t_2

An expression for the distance traveled during a glide can be obtained from this equation by letting $X = 0$ when $t_1 = 0$, and $X = X$ when $t_2 = t$ (where X = distance traveled, ft).

Substituting $\dot{X} = V_2$ and solving the equation,

$$X = (2m_L/D'\rho)\ln[(V_1 D'\rho t/2m_L) + 1]$$

If the porpoise glides through three hoops spaced at a distance X_Δ, this last expression can be modified to yield the following equation:

$$D' = (2m_L/\rho X_\Delta)\ln(\Delta t_2/\Delta t_1)$$

where

t_1 = time between first pair of hoops

t_2 = time between second pair of hoops

It is interesting to note from the earlier equation of D' that it is possible to obtain D' graphically by plotting $1/V$ versus time, since

$$D' = \frac{2m_L}{\rho}\left(\frac{1/V_2 - 1/V_1}{t_2 - t_1}\right) = \frac{2m_L}{\rho}\left(\frac{d/V}{dt}\right)$$

Hence, D' is proportional to the slope of $1/V$ versus time.

ACCELERATION

The differential equation

$$HP_a = m_L \dot{V} V/550$$

can be modified to yield

$$HP_a = (m_L/1,100)(dV^2/dt)$$

Therefore, if V^2 is plotted versus t, the slope of the curve quickly indicates the runs with peak acceleration power. It was found desirable to use this method to obtain acceleration horsepower since the data can easily be studied on the graph and faired, when justified.

The above equation can be solved to provide the following expression:

$$HP_2 = (m_L/1,100)[(V_2^2 - V_1^2)/(t_2 - t_1)]$$

TOP SPEED

Assuming the acceleration is zero at the recorded top speed, the drag horsepower, as shown earlier, is

$$HP_{D_{max}} = \frac{D'\rho V_{max}^3/2}{550}$$

Therefore, if D' and V_{max} are known, the maximum drag horsepower can be calculated. Conversely, the maximum total horsepower of the porpoise being known, the effective D' of the porpoise in the swimming state can be calculated if V_{max} is measured.

JUMPING

The height of a porpoise's jump is determined analytically by equating the potential energy at the peak of the jump to the kinetic and potential energy at water emergence. This value of energy results from the integral of $Pd\tau$, while the porpoise is accelerating underwater in preparation for the jump. This integral, $\int Pd\tau$, can be equated to the average power output, P_{av}, multiplied by the acceleration period, t_a.

$$m_o gh = (m_o V_e^2/2) + m_o gh_e = \int_0^{t_a} Pd\tau \approx P_{av} t_a$$

where

h = maximum height of the center of gravity (c.g.) of the porpoise above water, ft

V_e = water-exit velocity when the tail emerges, ft/sec

h_e = height of c.g. above water when the tail emerges, ft

P = power at time t, ft-lb

t_a = period of acceleration, sec

P_{av} = average power expended during time t_a

If the average velocity during the underwater acceleration period is $V_e/2$, then

$$t_a \approx 2s/V_e$$

where

s = distance traveled during acceleration, ft

Combining the equations and modifying them,

$$h = (V_e^2/2g) + h_e$$

$$V_e = \sqrt{2g(h - h_e)} = 8.02\sqrt{h - h_e}$$

$$P_{av} \approx m_o gh/t_a$$

If underwater photographs can be obtained of the acceleration period before the jump, the power can be calculated as in the previous discussion on acceleration.

ESTIMATED DRAG

The drag of the bare porpoise, the porpoise with collars, and the wave drag due to the proximity of the water surface are estimated in Appendixes A, B, and C, respectively. Estimates of the bare porpoise drag were made for full turbulent flow, full laminar flow, and 40% laminar flow at porpoise speeds of 10, 20, and 30 ft/sec. Estimates of the drag for the porpoise with a collar were made at the same three speeds, and it was assumed that the boundary layer was turbulent behind the collar. The wave drag of the porpoise was found to be negligible at speeds above 20 ft/sec for centerline depths of 2 feet or greater. At a depth of 2 feet, for instance, the wave-drag area, D', is 0.050 ft^2 at 10 ft/sec, 0.027 ft^2 at 12 ft/sec, 0.014 ft^2 at 14 ft/sec, and is negligible at 20 ft/sec and above. Figure 5 summarizes the drag-area estimates for the various configurations and shows the wave drag at run depths of 2 and 3 feet.

RESULTS

Table 1 presents a summary of the runs, and gives the date, time, collar thickness, number of hoops entered, maximum velocity, maximum acceleration horsepower and associated speed,

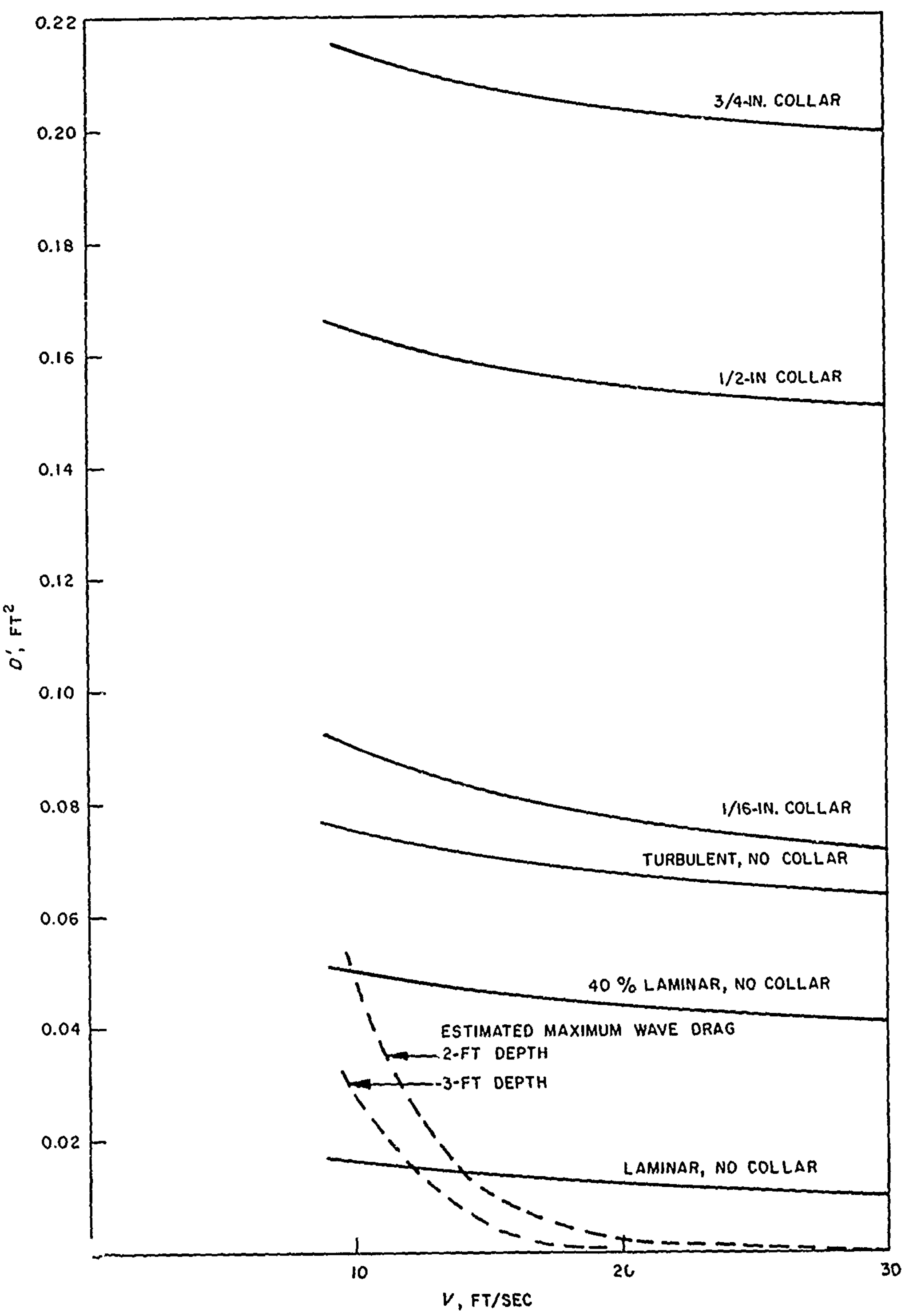


FIG. 5. Drag-Area Estimates.

TABLE 1. SUMMARY OF VALID PORPOISE RUNS

Date, 1960	Run no.[a]	Hour of run	Collar used, in.	Hoops, no. entered	V_{max}, ft/sec	Acceleration		Glide		Surfaced	Camera malfunction
						HP_a	V_{av}, ft/sec	D', ft^2	V_{av}, ft/sec		
3 June (water level 4.5 ft, slightly cloudy)	3-1	......	None	....	21.1	1.305	19.7	......	......	No	No
	3-5	......	1/2	....	8.3	......	......	......	......	Once	No
4 June (water level 4.5 ft, slightly cloudy)	4-1	......	None	....	25.1	1.430	23.0	......	......	Sta. 6	No
	4-2	......		....	17.9	0.255	17.6	......	......	No	Sta. 4
	4-3	......		....	19.3	1.175	15.7	......	......		No
	4-5	......		....	20.9	0.659	19.0	......	......		No
	4-6	......		....	15.9	0.242	13.9	......	......		Sta. 4
	4-7	......		....	17.7	0.572	16.9	......	......	Sta. 3 & 6	No
	4-8	......		....	18.0	0.414	16.4	......	......	Sta. 6	Sta. 4
	4-13	......		....	21.0	0.253	20.4	......	......	No	No
	4-14	......		....	18.3	0.699	10.2	......	......		
	4-15	......		....	18.6	0.631	17.4	......	......		
	4-16	......		....	17.2	0.510	15.5	......	......		
	4-17	......		....	15.6	0.608	11.3	......	......		
	4-18	......		5	15.4	......	......	0.043	14.9		Sta. 4
	4-19	......		5	13.4	......	......	.048	13.0		Sta. 4
	4-20	......		4	12.1	......	......	.058	11.6		Sta. 4
	4-22	......		4	12.0	......	......	.010	11.9		No
								.030	11.5		
	4-23	......		4	15.4	......	......	.056	14.7		
								.058	13.5		
	4-26	......		4	14.1	......	......	.005	14.1		Sta. 4
	4-27	......		4	14.0	......	......	.064	13.4		No
	4-28	......		4	12.1	......					
							......	.010	14.9		
								.044	11.5		
	4-29	......		4	14.2	......	......	.064	13.5		
								.005	12.8		
	4-30	......		4	13.4	......	......	.064	12.8		
								.064	11.6		
	4-32	......	1/2	3	12.7	......	......	.029	12.5		
5 June (water level 4.5 ft, slightly cloudy, water temp. 71°F)	5-1a	1030	None	....	22.0	1.538	16.5	......	......		
	5-1g	1035		4	14.1	......	......	.0698	13.4		
	5-2	......		4	12.2	......	......	.0225	12.1		
	5-3	......	3/4	3	11.5	......	......	.1444	10.3		
	5-4	......		3	10.2	......	......	......	......		Sta. 3
	5-5	......		....	17.9	0.025	17.8	......	......		No
	5-6	......		3	7.9	......	......	.0540	7.5		
	5-14	......	1/2	3	10.9	......	......	.0417	10.5		
	5-15	......		4	12.1	......	......	.0223	11.9		
								.0613	11.2		
	5-17	......		4	12.6	......	......	.0232	12.4		
								.0562	11.7		
	5-18	......		4	12.5	......	......	.0750	11.8		
								.0920	10.5		
	5-19	......		4	13.4	......	......	.0409	15.1		
								.0996	11.7		

TABLE 1. (Contd.)

Date, 1960	Run no.[a]	Hour of run	Collar used, in.	Hoops, no. entered	V_{max}, ft/sec	Acceleration		Glide		Surfaced	Camera malfunction
						HP_a	V_{av}, ft/sec	D', ft^2	V_{av}, ft/sec		
5 June	5-20	......	3/4	4	12.2	......	......	0.0859	11.5	No	No
	5-21	......		3	11.3	......	......	.0238	11.1		
	5-22	......		4	12.1	......	......	.0514	11.7		
								.1285	10.4		
	5-23	......		3	12.5	......	......	.0522	12.1		
	5-25	......		4	12.6	......	......	.0850	10.9		
								.0563	12.1		
								.1414	10.5		
	5-26	......	1	3	11.3	......	......	......	......		Sta. 3 & 4
	5-27	......		3	11.4	......	......	.0694	10.8		No
	5-28	......		3	11.1	......	......	.0694	10.5		
	5-29	......		4	12.9	......	......	.0419	12.5		
								.1301	11.1		
	5-30	......		4	11.2	......	......	.0968	11.1		
								.1349	10.1		
	5-31	......		3	11.8	......	......	.0473	11.4		
	5-33	......		3	11.3	......	......	.0633	10.8		
	5-34	......		3	11.2	......	......	.0591	10.7		
	5-35	......		3	11.6	......	......	.0324	11.3		
	5-36	......		3	11.2	......	......	.0865	10.6		
	5-37	......		3	9.8	......	......	.0740	9.2		
	5-38	......		3	10.9	......	......	.1631	9.8		
	5-39	......		3	10.6	......	......	.2056	9.2		
	5-40	......		4	10.4	......	......	.1406	9.4		
								.1642	7.5		
	5-42	......	None	....	20.1	......	......	......	......		
15 June (water level 6.0 ft, clear)	15-1	1230		....	20.2	0.189	17.3	......	......	Sta. 5 & 6	Sta. 2, no time
	15-2	1233		....	22.7	0.680	20.7	......	......	Sta. 5 & 6	
	15-3	1235	1/15	....	18.2	0.561	16.8	......	......	No	
	15-4	1239	1/16	.. .	17.8	0.308	16.3	......	......		
	15-5	1244	1/2	....	13.9	0.128	13.5	......	......		
	15-6	1317	None	....	24.7	0.927	22.2	.0342	22.2		
	15-7	1321	None	....	22.8	0.322	22.3	.0026	22.3		
								.0424	21.3		
								.0595	19.0		
	15-9	1325	3/8	....	12.6	0.024	12.3	.0217	12.3		
								.0269	11.7		
	15-11	1400	None	5	17.1	......	......	.0472	16.2		
								.0293	14.9		
								.0614	13.4		
	15-12	1406	None	5	18.7	......	......	.0645	17.4		
								0.0589	15.3		Sta. 9, no run Sta. 2, no time
	15-13	......	1/16	4	15.2	......	......	......	......		Sta. 2, no time Sta. 7, no run
	15-19	1445	1/16	4	16.5	......	......	. ....	......		Sta. 7, no run
	15-21	1510	3/4	....	13.2	0.334	11.6	......	......	Sta. 5	No
	15-22	1540	None	....	21.4	1.225	17.5	......	......	Sta. 5 & 6	No

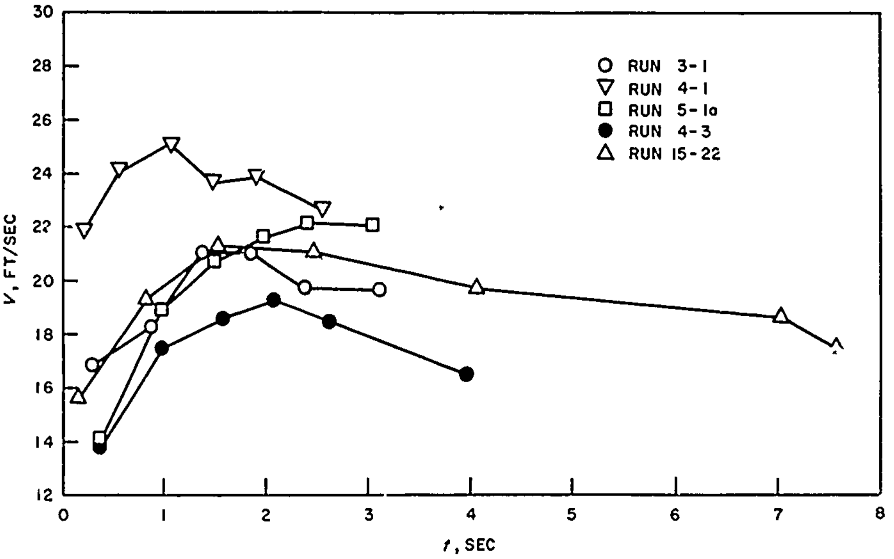
[a]Missing run numbers indicate runs in which the porpoise failed to make an adequate run, even though the cameras were operating.

maximum drag area and associated speed, comments regarding water depth and temperature, and miscellaneous notes. The numbering system adopted shows the day in June 1960 on which the test was conducted, followed by the number of the run on that day.

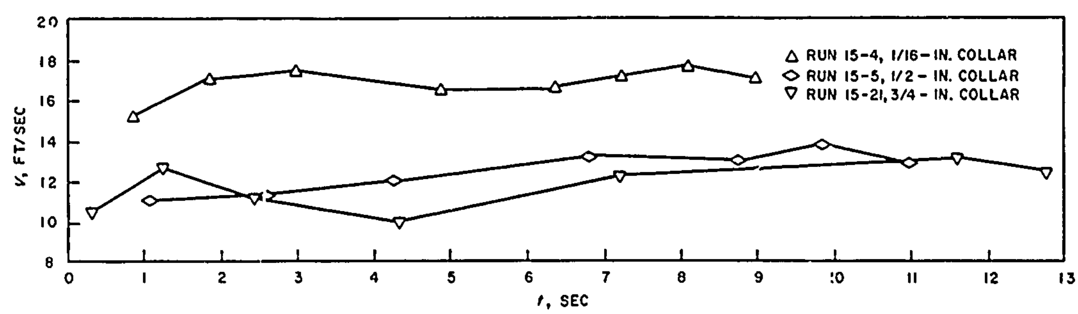
The film was examined to find the time the porpoise's nose crossed each distance mark, and average velocities from station to station were computed. Although the porpoise appeared in a large number of frames as it passed a camera, the surface distortion prevented the calculation of "instantaneous" velocities at the various stations. The time that the porpoise crossed the first definable station in each run was chosen to be the zero time for that run.

ACCELERATION POWER

Figure 6 shows velocity versus time for the runs, both with and without a collar, where the maximum acceleration power was recorded. Figure 7 shows these same runs plotted as V^2 versus t; the slope of this curve indicates acceleration power. Figure 8 is a summary of these runs showing the acceleration horsepower versus average speed.

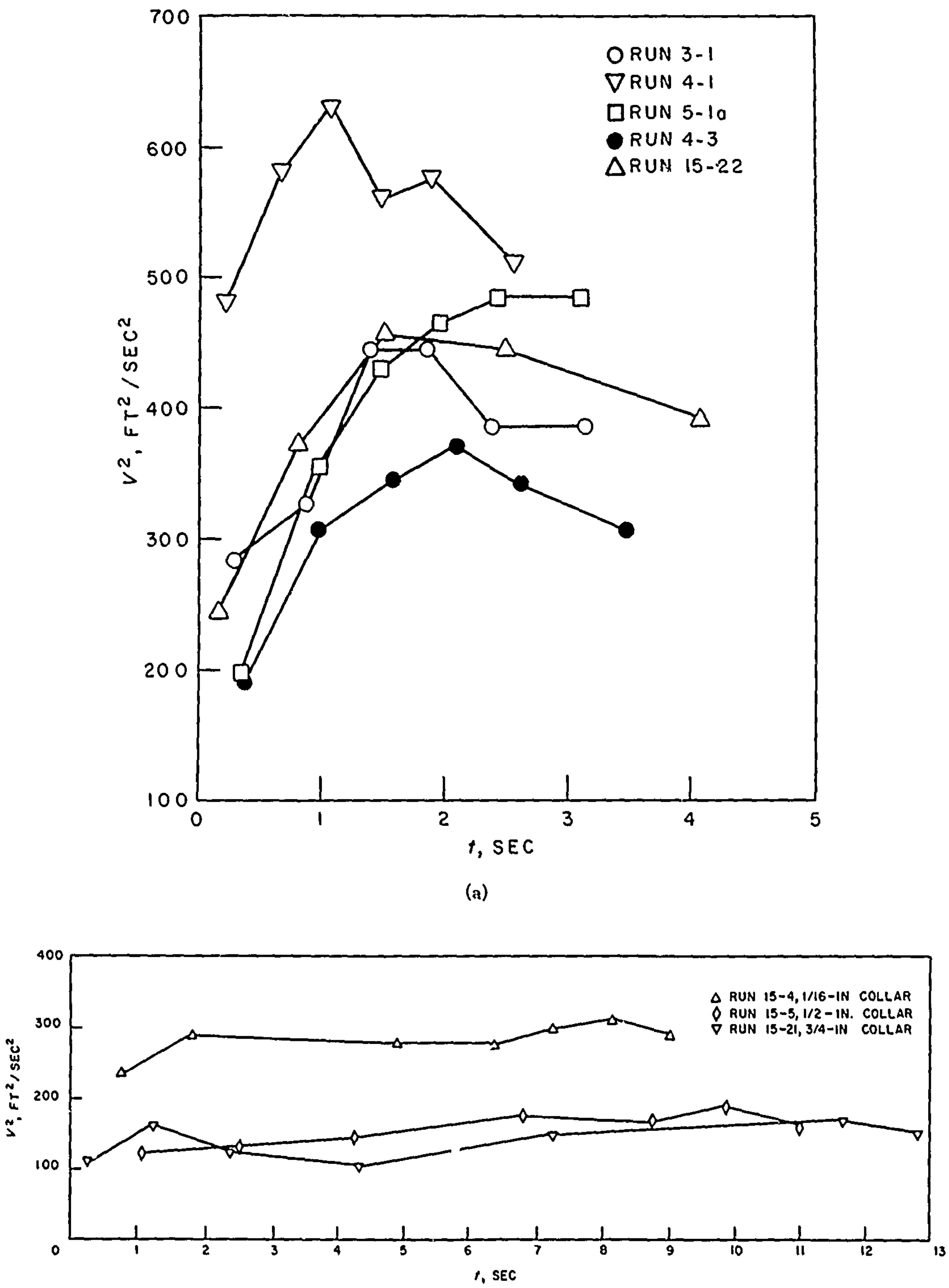


(a)



(b)

FIG. 6. Velocity Versus Time, for Maximum hP_a Runs. (a) Without collar; (b) with collar.



(b)

FIG. 7. Velocity Squared Versus Time, for Maximum HP_a Runs. (a) Without collar; (b) with collar.

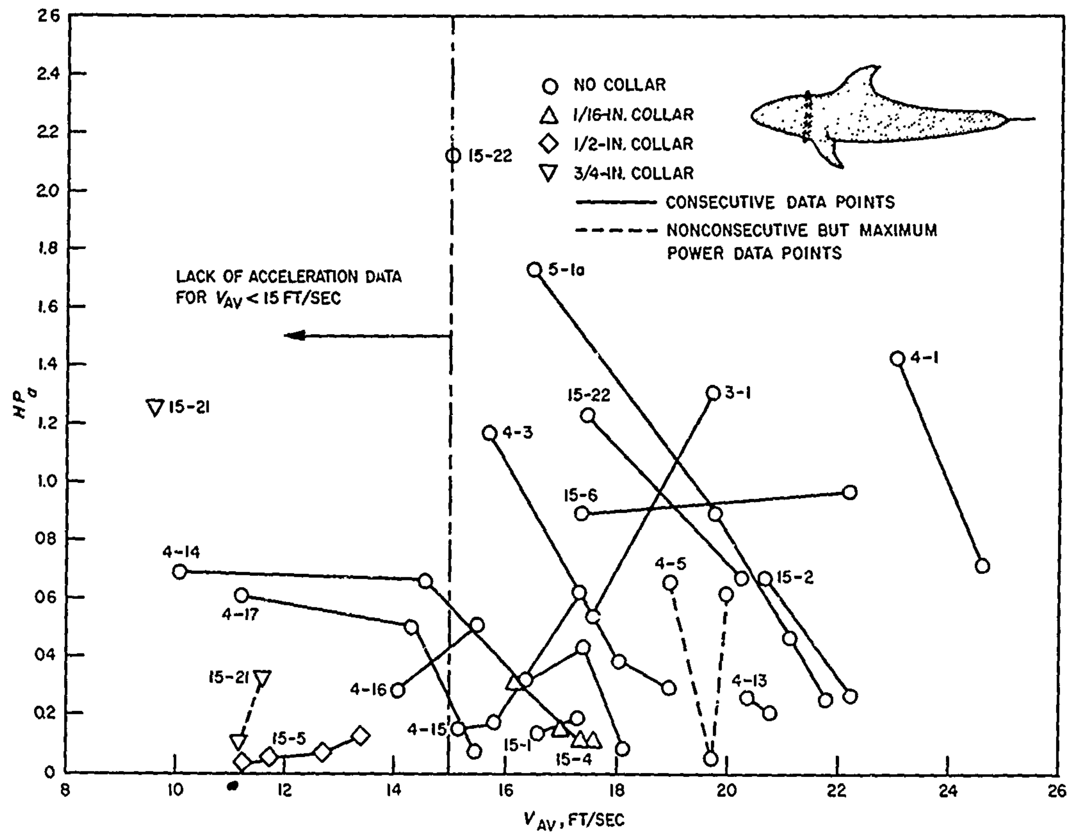


FIG. 8. Acceleration Horsepower Versus Average Speed, for Maximum HP_a Runs.

DRAG

Figure 9 is a graph of velocity versus time for the glide runs where the porpoise, with and without collars, traveled through a series of underwater hoops. Figure 10 is a plot of inverse velocity versus time for these same runs. The slope in this graph is proportional to the drag area

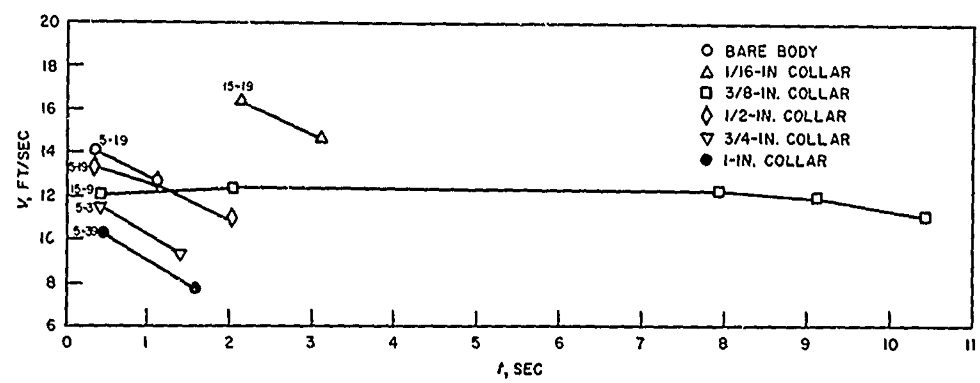


FIG. 9. Velocity Versus Time, for Glide Runs, Through Hoops, With and Without Collar.

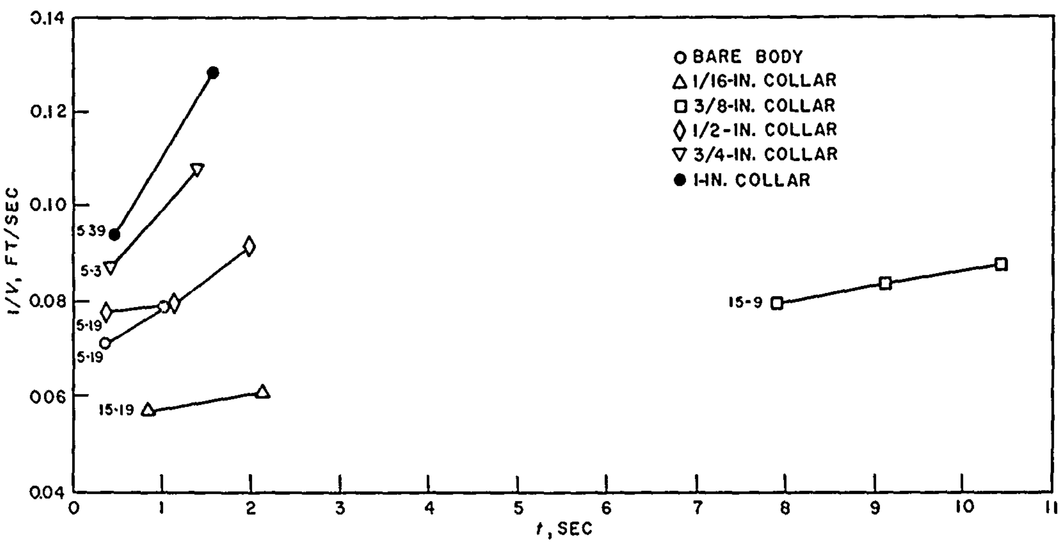


FIG. 10. Inverse Velocity Versus Time, for Glide Runs, Through Hoops, With and Without Collar.

of the gliding porpoise. Figure 11 is a plot of the various drag areas, measured with and without collars, versus the average speed of the porpoise during the glide. Tail movement was seen in all of the glide runs where D' is less than 0.04 ft^2, indicating that the porpoise was most likely producing thrust, so these points are not valid. Slight tail movement probably occurred during many of the other runs, but could not be detected because of the surface distortion caused by waves. Figure 12 shows the same drag areas as in Fig. 11, but plotted against collar thickness. The broken-line curve is a fairing of the maximum experimental D' data points. It is believed that this curve approaches the actual drag, since tail or body movement would most likely be used for acceleration; also, this curve agrees well with the predicted values of Appendixes A, B, and C. It is noted in Fig. 11 that the porpoise seldom permitted its speed to drop below 10 ft/sec; therefore, it is likely that, before its speed reduced to 10 ft/sec, the porpoise would tend to accelerate, rather than decelerate, to get through a series of hoops. It is noteworthy that the D' data points cluster and approach a maximum value; this value is most likely some kind of a fundamental, fixed parameter, such as the porpoise's drag.

TOP SPEED AND DRAG HORSEPOWER

Figure 13 shows velocity versus time for those runs where the maximum velocity was recorded, with and without collars. Figure 14 is a summary of runs showing top speed versus collar thickness. It is noted that a number of runs are required to show a trend of top speed versus collar thickness. One run with a given collar is inadequate for obtaining top speed. Figure 15 is a plot of drag horsepower versus collar thickness. The drag horsepower has been calculated using the faired experimental D' curve from Fig. 12 and the top speeds from Fig. 14.

PORPOISE MOVEMENTS

It is interesting to study the porpoise's movements while it is swimming. Figure 16 is a tracing from motion picture frames of the porpoise during a typical acceleration run. The super-

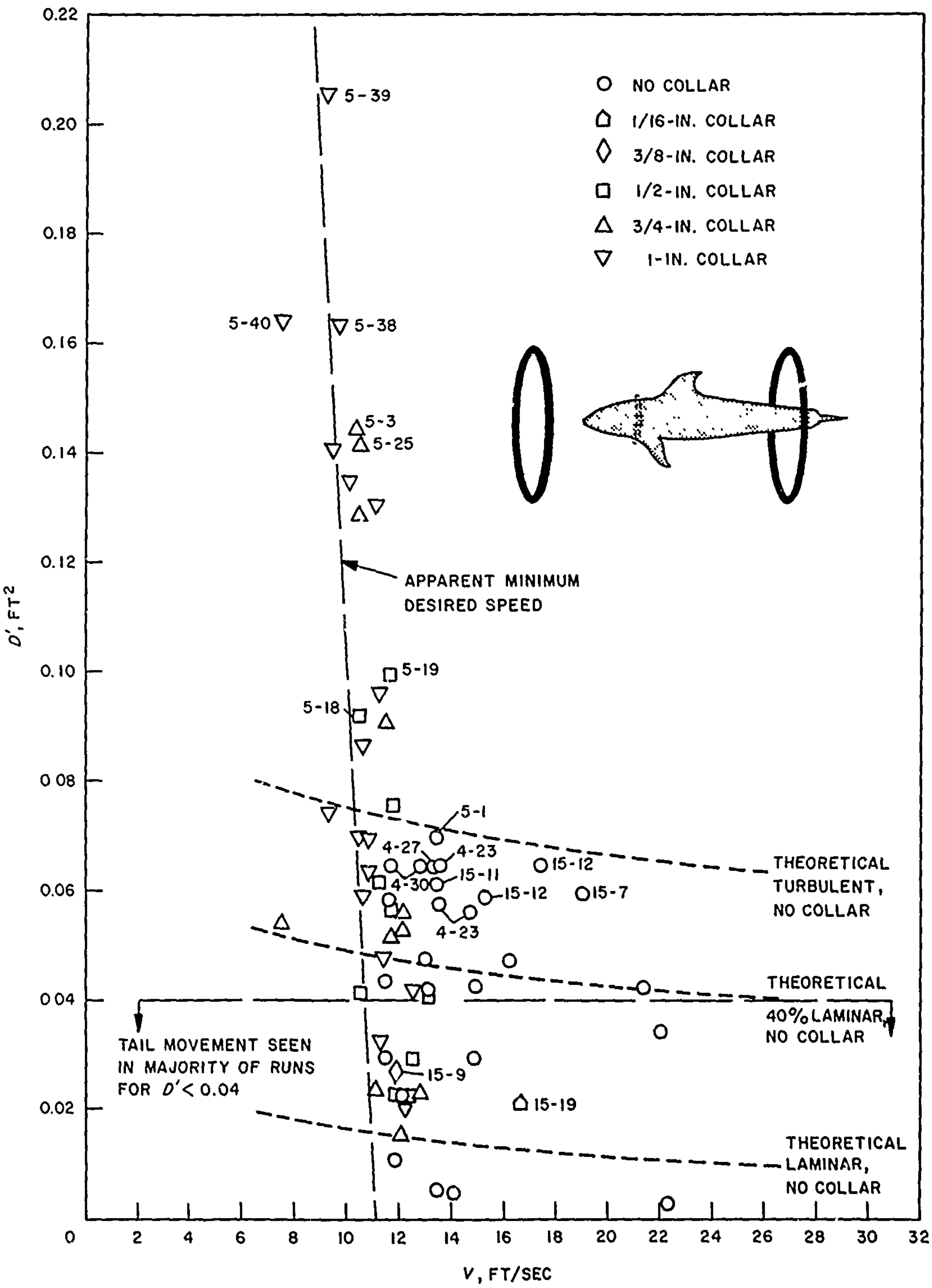


FIG. 11. Drag Area Versus Average Speed During Glide, Through Hoops, With and Without Collar. Run numbers are shown for the more important data points.

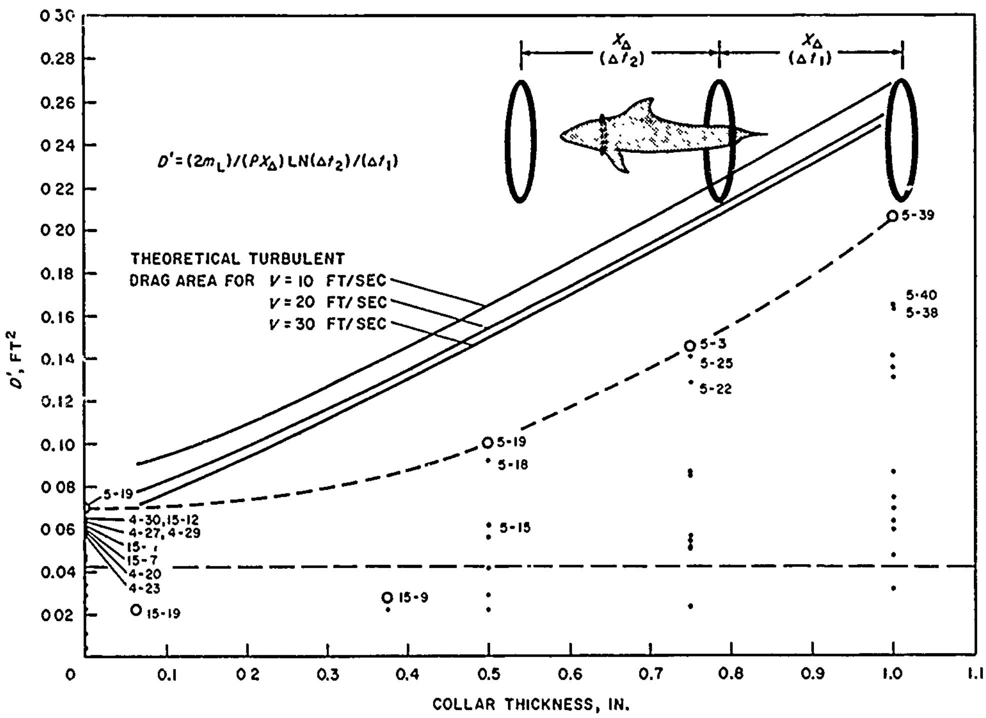


FIG. 12. Drag Area Versus Collar Thickness, for Glide Runs, Through Hoops, With and Without Collar. The dotted curve is a fairing of the maximum experimental D' data points. Tail movement definitely seen in all runs below 0.04 and in many above.

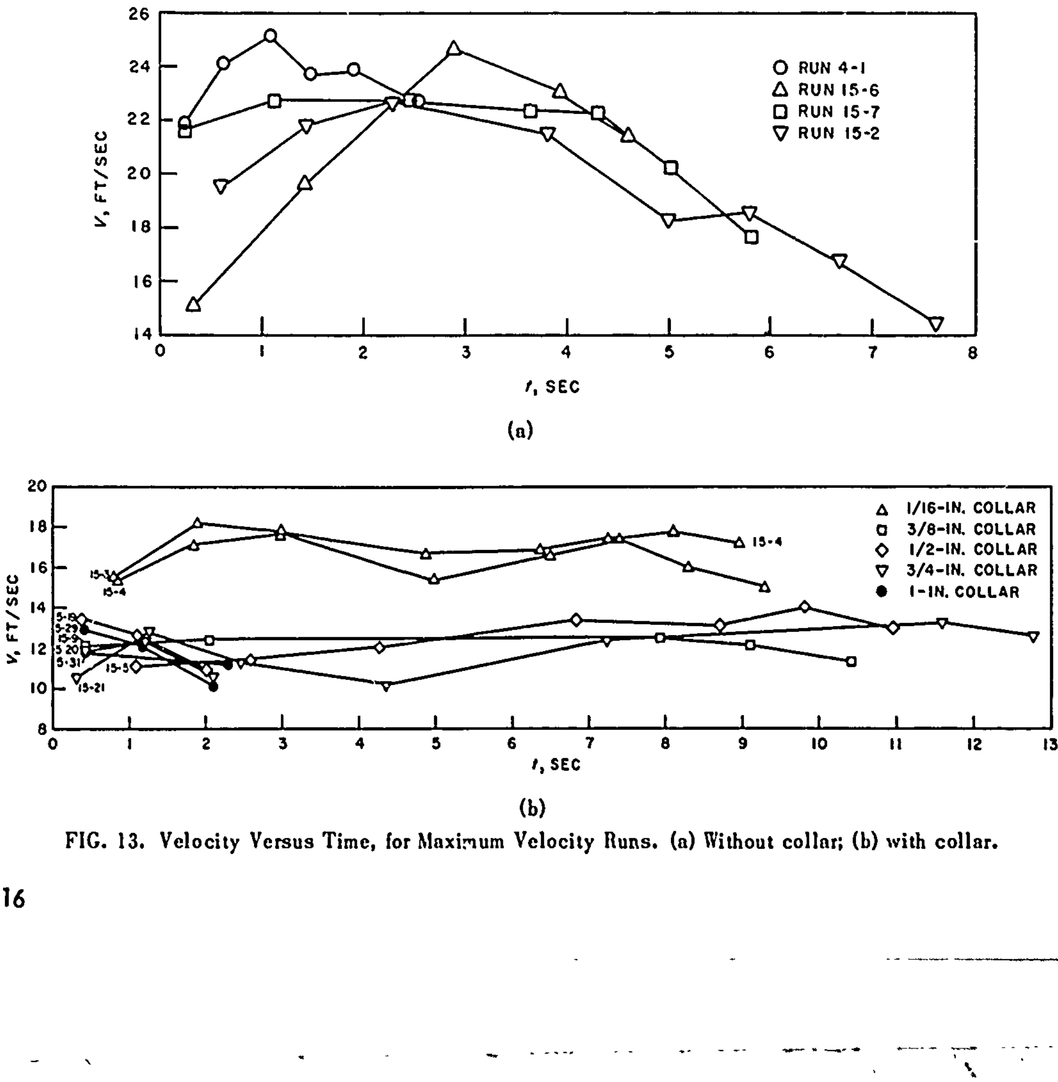


FIG. 13. Velocity Versus Time, for Maximum Velocity Runs. (a) Without collar; (b) with collar.

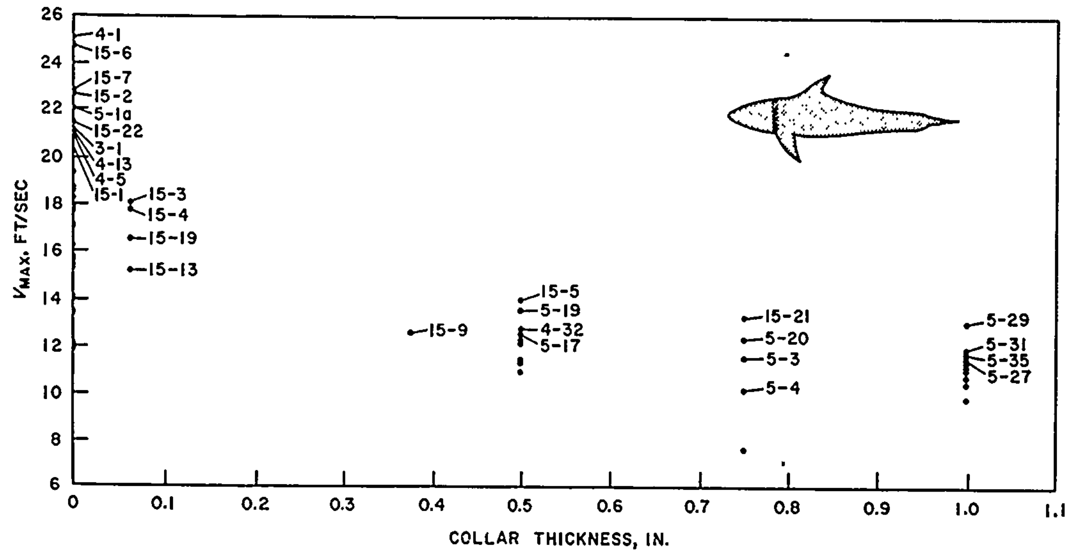


FIG. 14. Top Speed Versus Collar Thickness.

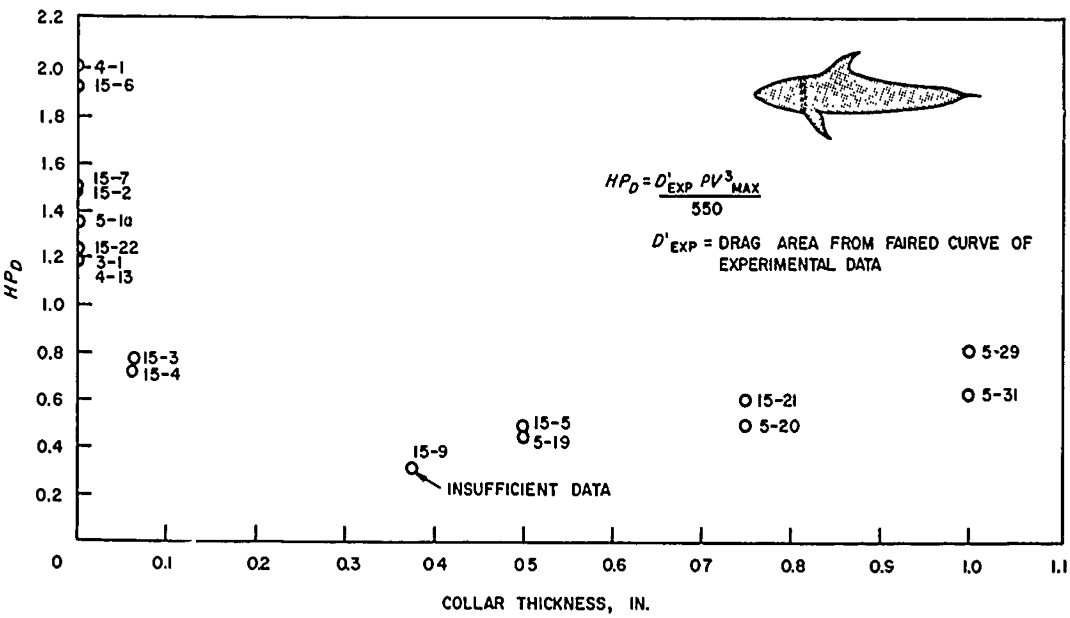


FIG. 15. Drag Horsepower Versus Collar Thickness.

imposed tracings show the relative body and tail angles and their paths during two cycles. It is seen that the cycle length is slightly less than the porpoise length. To indicate the angular movements of the body and tail during a typical cycle, Fig. 17 shows the porpoise body and tail superimposed and the nose station aligned. Figure 18 shows nose and dorsal velocities versus distance traveled, for runs 15-21 and 15-22. It is of interest to note that the nose velocities provide a rel-

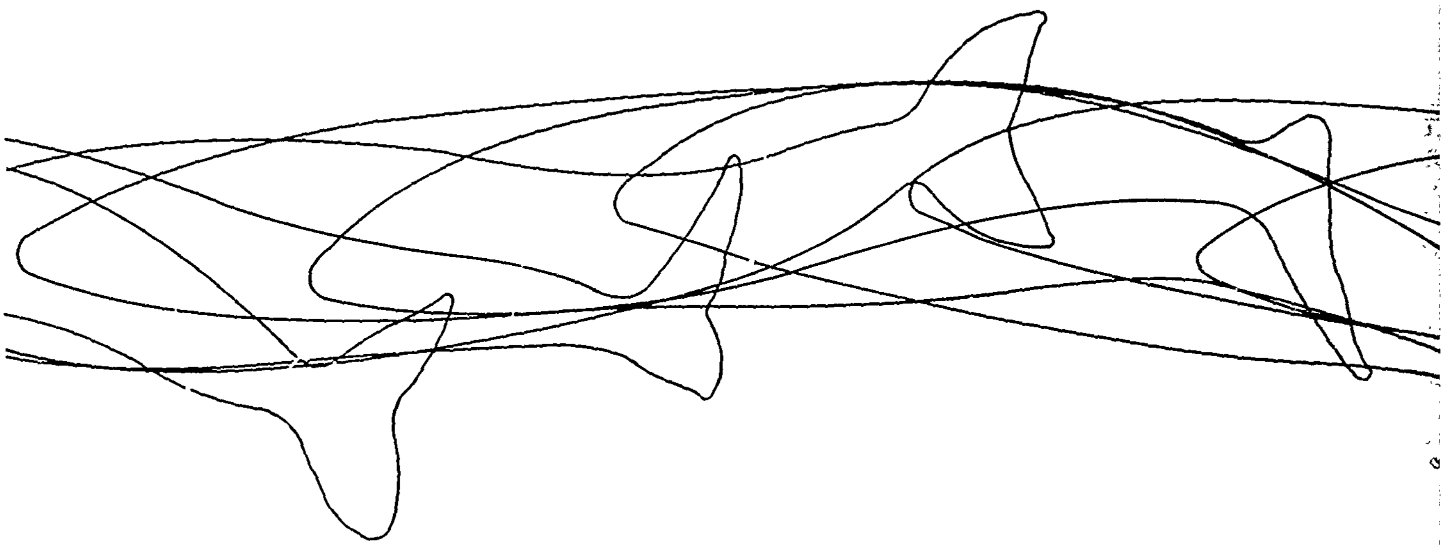
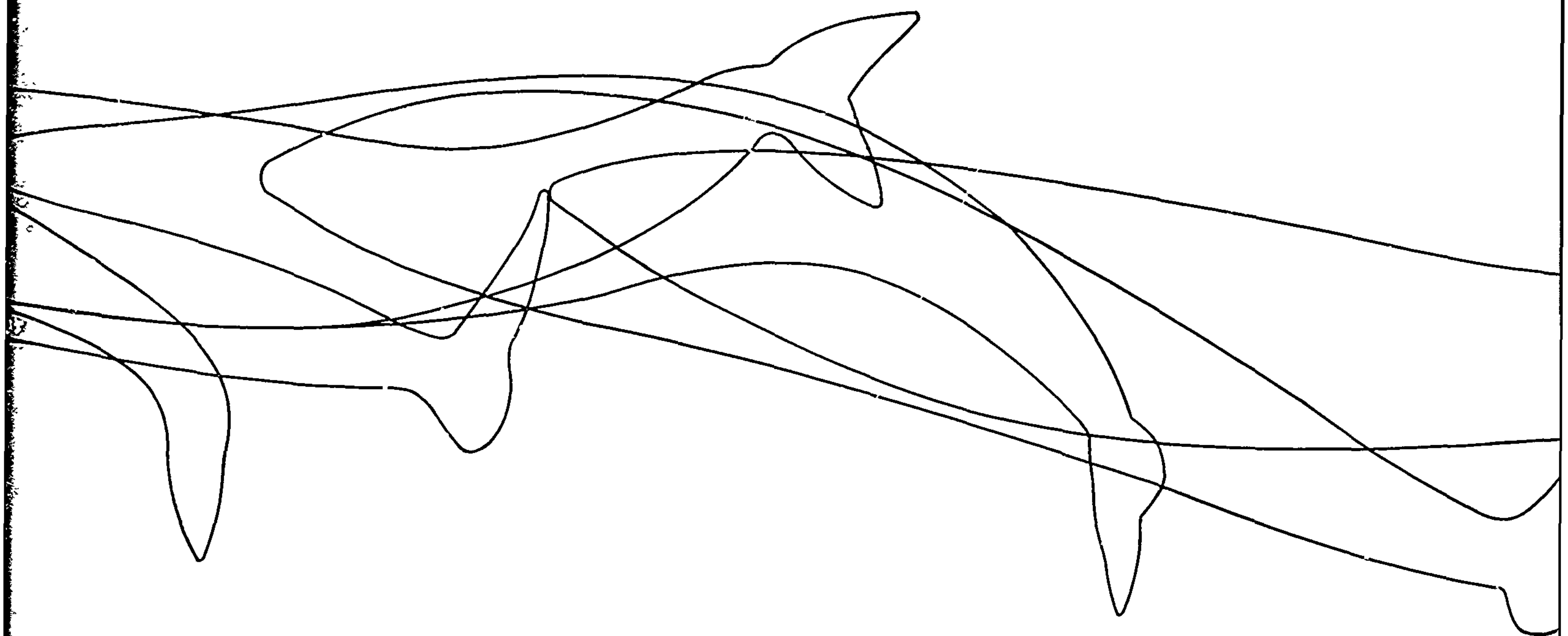


FIG. 16. Porpoise Movements Du
Traced from film, 14 frames apart



During Acceleration (Run 15-21), With 3/4-Inch Drag Collar.
art (approximately 0.2-second intervals).

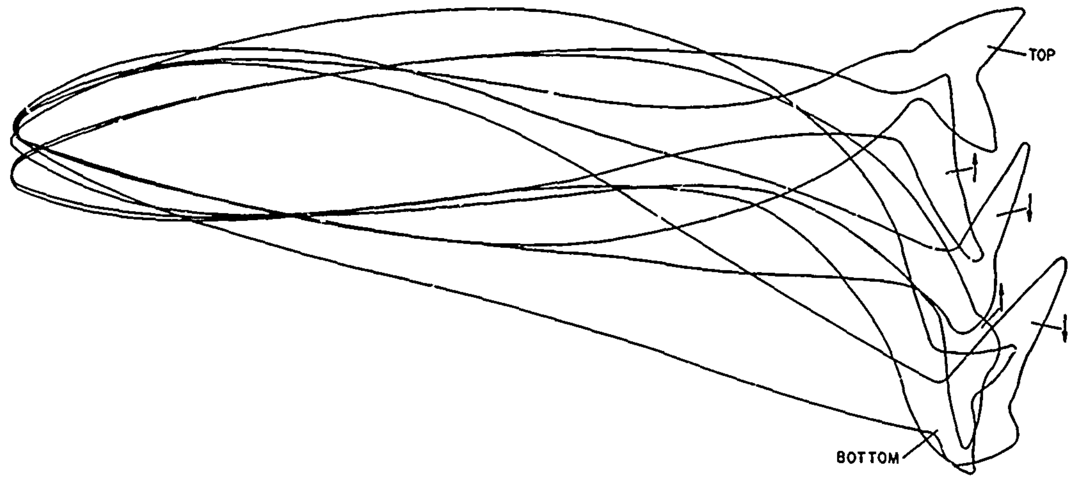


FIG. 17. Porpoise Movements During Acceleration (Run 15-21), With 3/4-Inch Drag Collar, Nose Stations Aligned. Time intervals between pictures not equal.

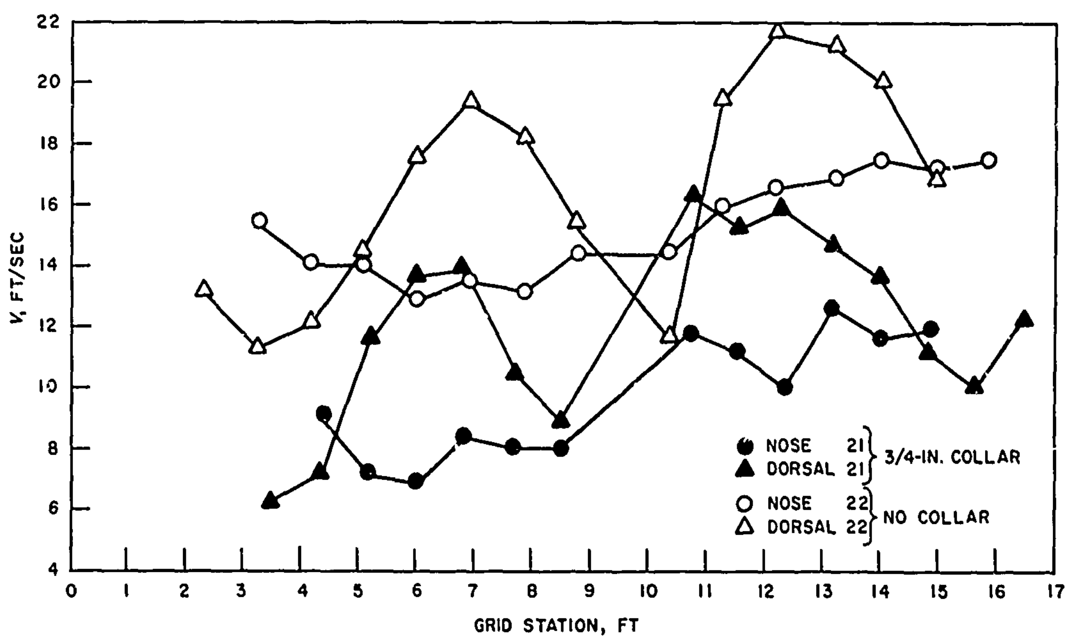
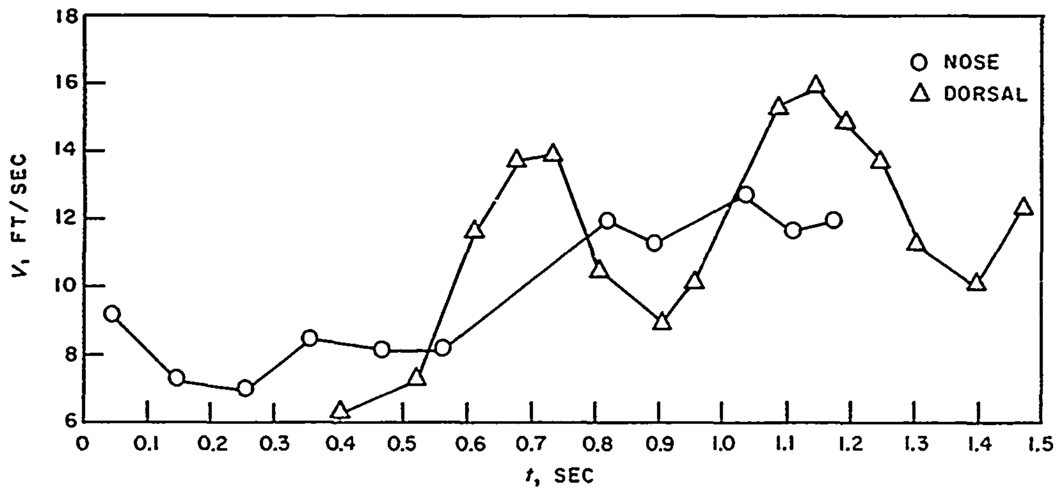


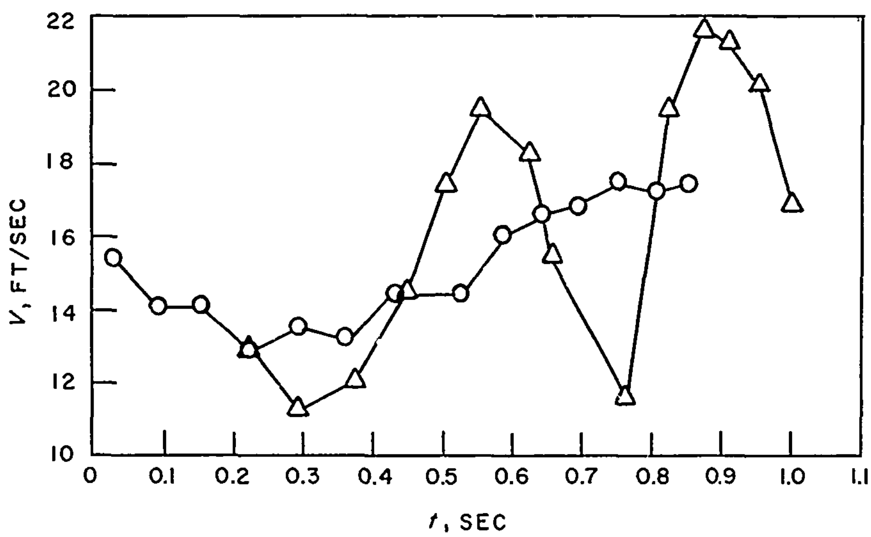
FIG. 18. Nose and Dorsal Fin Velocities Versus Grid Station, for Runs 15-21 and 15-22. Nose velocity measured as nose crosses grid; dorsal fin velocity as dorsal fin crosses grid.

atively linear measurement of velocity while the dorsal-tip velocities show cyclic effects caused by body rotation. In view of Fig. 16, 17, and 18, it can be seen that the nose is the best station for obtaining position data. Figure 19 shows velocity versus time for runs 15-21 and 15-22 and

further verifies this conclusion. Figure 20 shows the path of the tail base, tail angle of attack, and timing marks for runs 15-21 and 15-22. The tail angles of attack were difficult to measure and may therefore be represented somewhat inaccurately. Figure 21 shows schematically the shape of the body and tail during acceleration for runs 15-21 and 15-22.

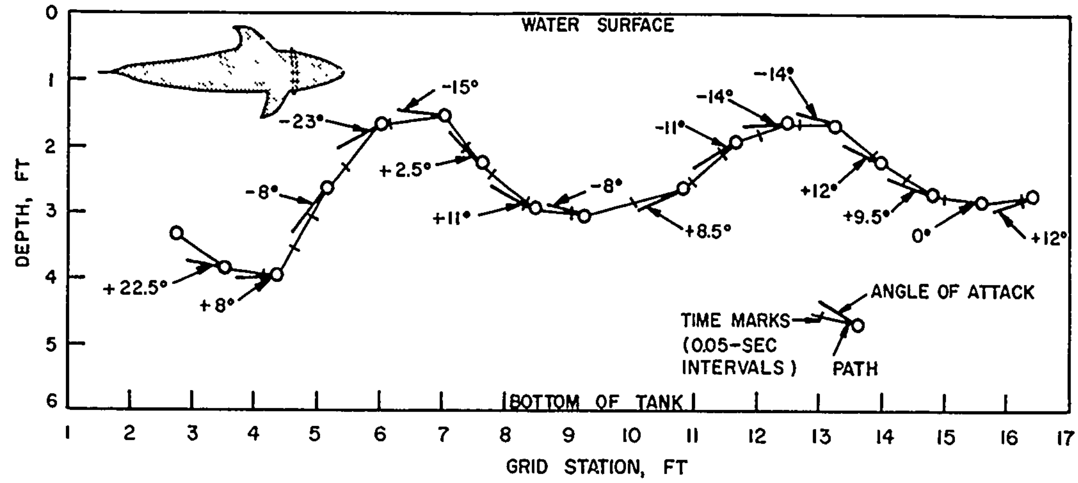


(a)

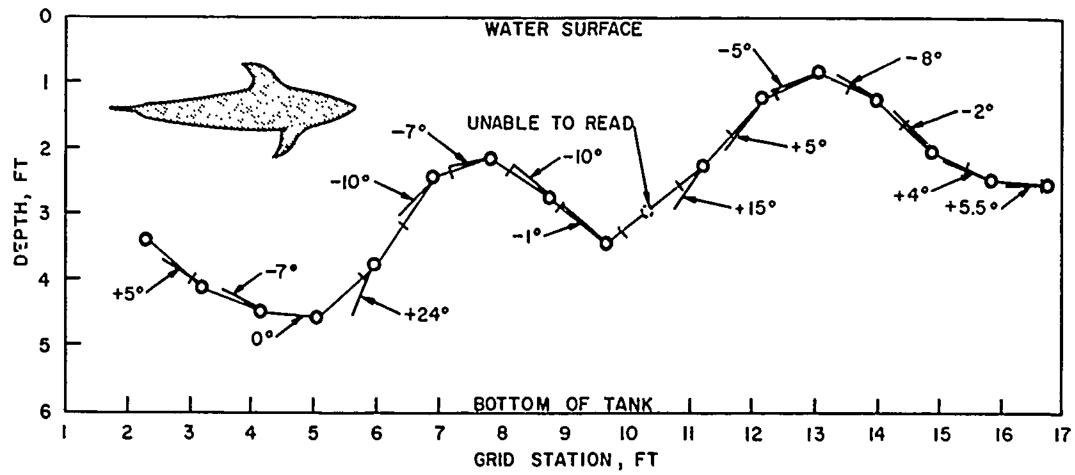


(b)

FIG. 19. Nose and Dorsal Fin Velocities Versus Time. (a) Run 15-21; (b) run 15-22.

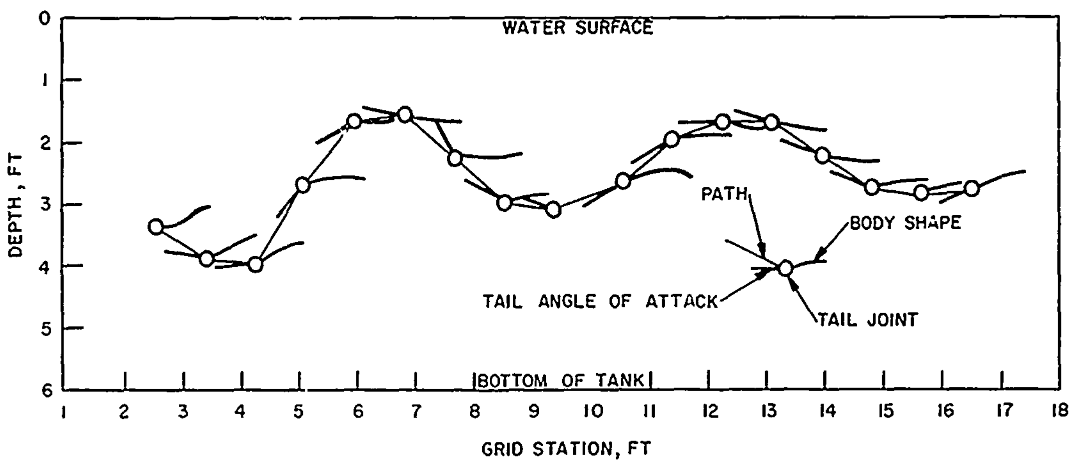


(a)

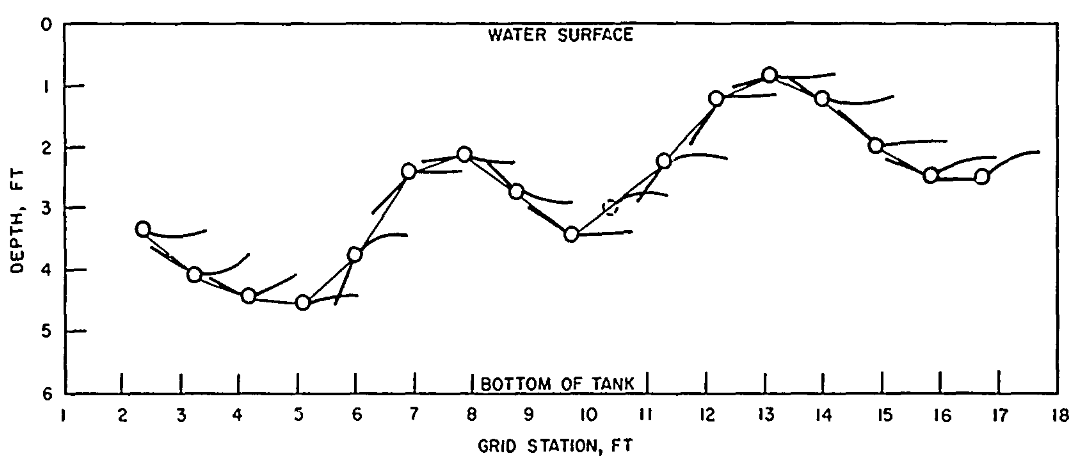


(b)

FIG. 20. Path of Tail Base. (a) Run 15-21; (b) run 15-22.



(a)



(b)

FIG. 21. Path of Tail Base and Schematic Body Shape. (a) Run 15-21; (b) run 15-22.

ANALYSIS

PRELIMINARY CONSIDERATIONS

In analyzing the results of these experimental runs, the most important consideration becomes the fact that the tests were conducted using a live animal, which means that

1. The power output when exerting maximum effort varies with time.
2. Rest periods between runs are important.
3. Training is limited because of communication difficulties, which casts doubt as to whether peak effort was ever exerted. Also, owing to body movement, glide runs may not provide valid drag data.
4. Psychological effects influence performance.
5. Physiological effects influence performance.

BOUNDARY LAYER STATE

The question of a laminar versus a turbulent boundary layer immediately arises. It can be seen in Fig. 12 that the curve faired through the experimental drag data shows no sharp discontinuity between the runs with collars and those without. It is well known in the literature that a 1/16-inch-thick collar will induce a turbulent boundary layer behind it, as will all thicker collars. The calculated drag plotted in Fig. 5 shows a great difference in drag between laminar and turbulent flow. If the boundary layer was turbulent, very little difference in drag would result from adding a 1/16-inch collar. Therefore, the results strongly indicate that the boundary layer was primarily turbulent before the collar was added. Of course, the wave drag may have influenced the experimental data. Figure 5 shows that for a depth of 2 feet the wave drag increases D' about 0.027 ft^2 at 12 ft/sec and 0.01 ft^2 or less at speeds greater than 15 ft/sec. This estimate of wave drag is pessimistic because it is based on an infinite channel depth. Using the preceding values for wave drag, it is seen that D' for the porpoise without collars and without wave drag cannot be less than 0.04 ft^2. As shown by runs 15-12 and 15-7 in Fig. 11, the value of D' is most likely around 0.055 to 0.060 ft^2, since the velocity was sufficiently high to make wave effects small. Therefore, according to the experimental results and the theory illustrated by Fig. 5, the boundary layer is probably around 20% laminar. An equivalent streamlined torpedo-like body would have around 30% laminar flow at 15 ft/sec, where the Reynolds number, R_ℓ, is 8×10^6, and perhaps 10% laminar flow at 25 ft/sec, where R_ℓ is 13×10^6. The mouth, eyes, and fin intersections on the porpoise could, of course, cause premature transition to turbulence, particularly if the water were turbulent.

Wind tunnel experiments have shown that if even 0.1% turbulence exists in the fluid medium, the boundary layer will become turbulent sooner than it would in the open atmosphere. Consequently, heat convection currents in the tank or water currents remaining from the previous passage of the porpoise could have made the boundary layer turbulent, whereas it may be laminar in the open ocean. Also, small particles suspended in the water can produce turbulence where laminar flow would otherwise exist. The possibility of water turbulence affecting the boundary layer is countered to a small extent by the fact that Notty's first run down the tank each day showed nothing unusual. The water was not entirely quiescent, however, since the filters were turned off only one-half hour before testing began.

POWER OUTPUT

In studying Fig. 8 and 15, which show the acceleration and drag horsepowers, respectively, it is noted that the peak measured horsepowers are comparable. The maximum acceleration horsepowers of the top four runs vary from 1.4 to 2.1. The maximum drag horsepowers of the top four runs with no collars vary from 1.4 to 2.0. It is important to remember that these drag horsepower values are not measured, as were the acceleration values, but are calculated from the top-speed measurement coupled with the experimental-drag measurement obtained during gliding. Thus, the assumption has been made that the drag is not influenced by body movement. The agreement between the two methods of measuring power tends to support this assumption.

Further study of Fig. 15 shows drag horsepower is less when collars were worn than when they were not. The maximum power with collars is 0.8 hp and without collars it is 2.0 hp. The higher value agrees with the results of the acceleration runs. Why is the power with collars only 0.8 hp? One reason, seen in Fig. 6, 7, and 13, is that the higher values of acceleration and no-collar drag power are reached for only 1 to 2 seconds, while the top-speed runs with collars lasted for several seconds. It is known that the power level of live animals reduces markedly as the exertion period increases. To demonstrate this fact, Fig. 22, which is reproduced from Ref. 4,

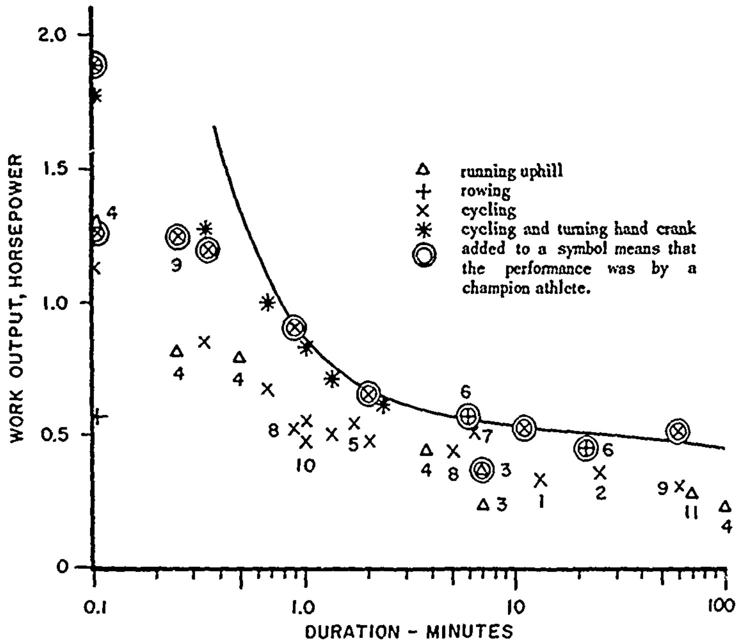


Figure 2. Maximal output of external mechanical power (h.p. linear scale) plotted against total duration of exercise (min. logarithmic scale). The logarithmic scale has been used to display the experimental points clearly. Full line is the theoretical curve shown in Fig. 1. The numeral indicates the source from which the experimental point was derived. Points without numerals: champion cyclists, ⊗ Ref. 21; ordinary cyclists, ×, also ordinary cyclist performing hand-cranking in addition,* Ref. 29.
1. Abbott *et al*; 2. Asmussen; 3. Bannister; 4. Benedict *et al*; 5. Bonjor; 6. Henderson *et al*; 7. Karpovich *et al*; 8. Nielsen *et al*; 9. Raleigh; 10. Tuttle; 11. Unna.

Conclusion

It is deduced from the published literature that the usable external power output of the body is limited in the following manner for the reasons stated:

(1) In single movements (duration less than 1 sec.) to less than 6 h.p.; by the intrinsic power production of muscle, and by the difficulty of coupling a large mass of muscle to a suitably matched load.
(2) In brief bouts of exercise (0·1–5 min.) to 2–0·5 h.p.; by the availability in the muscles of stores of chemical substances that can yield energy by hydrolysis.
(3) In steady-state work (5 min. to 150 min. or more) to 0·5–0·4 h.p.; by the ability of the body to absorb and transport oxygen.
(4) In long-term work, lasting all day, to perhaps 0·2 h.p.; by wear and tear of muscles, the need to eat and so on.

All these figures refer to champion athletes; ordinary healthy individuals can produce less than 70–80 per cent as much power.

FIG. 22. Maximum Horsepower Versus Exertion Time for a Human. Reproduced from Ref. 4 with permission of D. R. Wilkie and the Royal Aeronautical Society.

is included. It shows the maximum horsepower versus exertion time for a human being. These tests were conducted after periods of rest. Note that trained athletes can produce 0.8 hp for 60 seconds, 1.8 hp for 6 seconds, or 6.0 hp for a fraction of a second. In view of this fact, Fig. 23 was constructed and shows maximum porpoise horsepower versus the approximate exertion period during which this power was applied. These data points are only approximate since a good deal of judgment was needed to evaluate the exertion periods. Also, the porpoise power that is plot-

ted is a combination of acceleration and drag power averaged over the exertion-time interval. All the porpoise power data should be increased, of course, to include the effect of hydrodynamic propulsive efficiency. The broken line in Fig. 23 is the envelope of peak porpoise power versus time, corrected for an assumed propulsive efficiency of 80%. This curve of porpoise power output agrees favorably with that for humans. The highest values of porpoise power were generally recorded on the first run of each day or after a rest period of 30 minutes. One or two exceptions are seen, however, as noted in Fig. 23.

Another reason for low drag horsepower with collars is that all the porpoise runs with collars were performed later in the run series on each day. In general, only short rest periods occurred between runs with collars. In view of this, the power data of the porpoise runs with collars compare favorably with those mentioned in Fig. 23 for humans, for extended periods.

A third reason for lower drag horsepower with collars might be that the collars may have hurt the porpoise when their drag increased beyond a certain amount; consequently, top speed with collars may not have been the peak-effort speed.

Another reason for low collar-drag horsepower might be that the faired curve of D' for the collars may have been too low. As shown in Appendix D, however, the measured D' is not far from the David Taylor Model Basin (DTMB) test results.

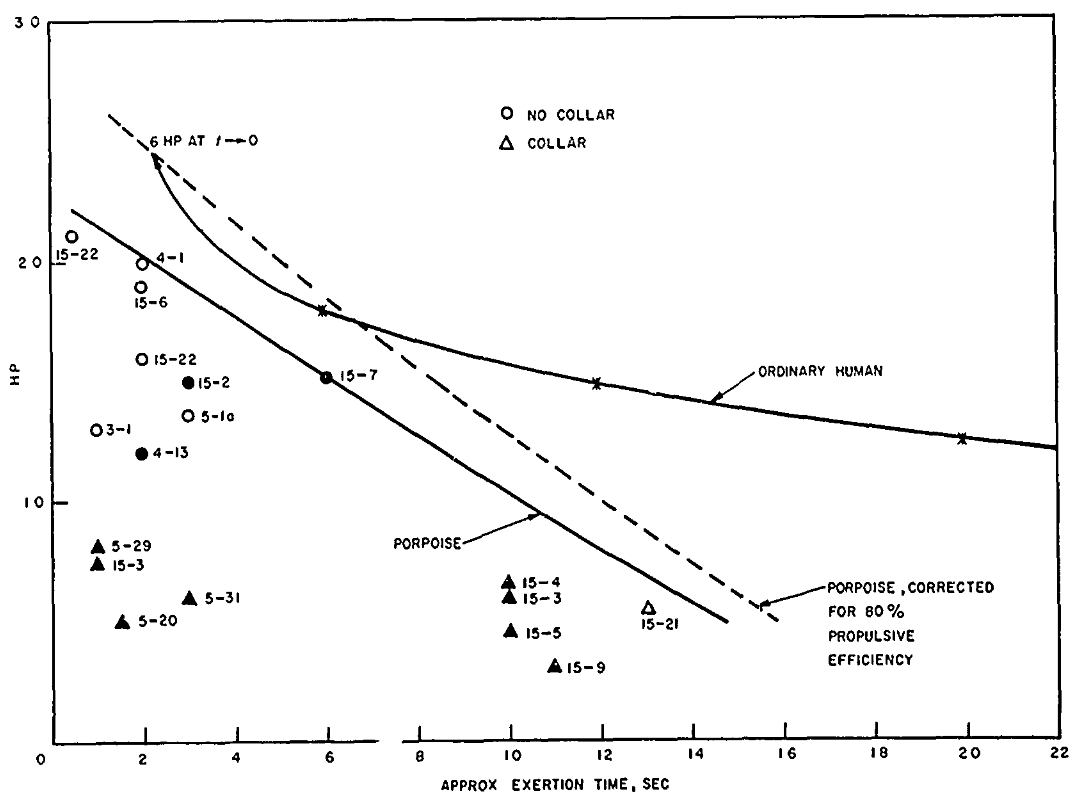


FIG. 23. Maximum Porpoise Horsepower Versus Exertion Time. Unshaded points refer to runs following rest periods of at least one-half hour.

Other possible reasons for low drag horsepower are that the propulsive efficiency of the porpoise may have been lowered because of high collar-drag and low speed; or that the extended runtime caused by the long channel and low speed made the porpoise reserve its strength like a long-distance runner, in contrast to the practice of a 100-yard-dash runner.

No power measurements around 6 hp were recorded for the porpoise as for humans. A possible reason is that, because of camera malfunction, very little data were gathered during the initial acceleration period, at which time the porpoise could have expended its ability to produce 6 hp. It is also conceivable that power levels approaching 6 hp might have been measured had more runs been recorded.

In summary, it is seen that the power output observed from the porpoise in this test program is comparable to that of human beings. It is reasonable, however, to expect the porpoise to produce slightly more power than humans, since all of the porpoise muscles are designed for the sole purpose of swimming, while human muscles are designed for multiple purposes. A wild porpoise can also be expected to perform like a trained athlete. It is conceivable that Notty's large food intake indicates a greater rate of metabolism than for a human being of equivalent weight. On the other hand, her power output may have been diminished because of her confinement after capture.

MISCELLANEOUS FACTORS AFFECTING TEST RESULTS

It may never be known whether Notty produced a maximum effort. All that can be said is that no unusual power output was observed. In addition to the previously stated reasons, it is possible that the tank was either too narrow or too short. It is likely that Notty could not stop or turn quickly at a high speed, even though she appeared to turn and stop with ease at the maximum observed speed of 15 knots.

Such boundary layer control mechanisms as body undulation, skin damping, and heat addition might have been controllable by Notty. Changing the blood pressure in the layer of skin, for instance, could change the damping characteristics of the skin or its heat transfer. It is possible that such a change must be made as a function of speed in order to lower the drag. If such control is needed and is voluntary, Notty may not have used it in view of the restricted tank length, or in view of some other factor. Also, theories and experiments on skin damping show that it is difficult to design a flexible skin that will operate over a large speed range. Consequently, it is possible that low drag would not be seen in the speed test range.

BODY AND TAIL MOVEMENTS

It is interesting to analyze the body and tail movements of the porpoise, as shown in Fig. 16 through 21, which are based on the data of runs 15-21 and 15-22. In Fig. 16 and 17 it is seen that body rotation and movement occurs in addition to considerable tail movement. This indicates that a portion of the thrust is probably generated by the body, in much the same way a fish generates thrust. However, the large size of the porpoise's tail, its great vertical movement. and its angle-of-attack changes during each cycle would indicate that a great deal of the total thrust is produced by the tail alone. Although the angles of attack of the tail, as shown in Fig. 20, are not accurate, they are generally in the direction expected to produce forward thrust. The tail angle of attack appears to be greater in run 15-21, where a 3/4-inch collar is used, than in run 15-22, with no collar. It is necessary that the porpoise undulate its body to counteract the pitch movement of the tail. However, since it is known that bodies can develop thrust by undulating, it is most probable that it uses body movement for both added thrust and pitch stability.

It is apparent in Fig. 18 and 19 that speed measurements obtained using the nose position are far superior to those obtained using the dorsal fin position. Although the data are limited,

the nose speed appears to be unaffected by the cyclic rotational motion of the body. A close inspection of Fig. 18 and 19 indicates that the nose acceleration is fairly uniform with time and not necessarily cyclic, as one would expect at first.

Of particular interest in these runs is the fact that the body shown in Fig. 17 is not excessively bent except during the upstroke of the tail, just after the tail has reached the bottom of its stroke. This excessive body bending is so rapid that the tail hardly moves during this period. This unsymmetrical motion is in contrast to the motion of fish, and is most likely due to the fact that the porpoise's backbone is located near the upper side of its body and the majority of its muscles are located near the lower side.

ANALYSIS OF THE PREDICTED AND OBSERVED SPEEDS OF PORPOISES, WHALES, AND FISH

It is interesting to analyze the documented top speeds of cetaceans and fish in the open ocean by making a comparison with predicted values, using the experimental drag coefficients of rigid streamlined bodies and the power output ratios of humans.

TOP-SPEED CALCULATIONS

To calculate the drag and speed of each size of cetacean or fish, it is assumed that its general shape can be approximated by a 6 :1 ellipsoid with an added tail region that extends the ellipsoid length 20%. The weight of each body is assumed to be that of the basic 6:1 ellipsoid of neutral buoyancy. The surface area of each body is assumed to be 20% greater than that of the basic ellipsoid, to account for the fins and the tail. The drag coefficients are those resulting from experimental tests on rigid, smooth, streamlined bodies, reported in Ref. 5 as a function of Reynolds number. These coefficients are seen on page 6-16 of Ref. 5 to include some of the effects of laminar flow, if the Reynolds number is below 2×10^7.

Since the porpoises' muscles are in daily use, it is possible that their power output per pound of total body weight is equal to that of trained athletes. Test results reported in Ref. 4 show that power output is considerably affected by the exertion period. It is quite likely, also, that their power output will be superior to that of humans because their muscles are designed for the sole purpose of swimming.

In view of the possibility of sea animals maintaining full laminar flow, calculations were also made using the experimental laminar flow drag coefficients of Ref. 5, extrapolated to higher Reynolds numbers.

The results of these calculations are shown in Table 2 and Fig. 24. Body weights ranged from 2 pounds for the smaller fish to 200,000 pounds for the blue whales. Included in Table 2 are the approximate lengths, surface areas, drag coefficients, power outputs, and top speeds as a function of body weight.

The solid lines in Fig. 24 are the estimated top speeds, using experimental human power and rigid-body drag data. The broken lines refer to the same conditions, except with full laminar flow. The two sets of lines converge in the weight range of 2 to 5 pounds, indicating that full laminar flow would normally be expected for fish of this size. It is interesting that, in spite of more turbulent flow, the expected top speed continuously increases as body size increases. Also, it is noted that, because of the crossover from laminar to turbulent flow, the top speed is fairly constant for body weights between 20 and 200 pounds. It must be remembered, however, that these calculations are simplified, and that the accuracy of the results suffers accordingly.

TABLE 2. ESTIMATED SPEEDS OF SUBMERGED RIGID BODIES WITH A POWER OUTPUT COMPARABLE TO THAT OF HUMANS

Weight, lb	Volume, ft^3	Length, ft	Surface area, ft^2	Exertion period	Horsepower	Drag coefficient	Velocity ft/sec	Velocity knots	Reynolds number
Part A. Expected Speed									
20	0.313	3.34	3.86	0.5 sec	0.70	0.0024	32.8	19.4	8.4×10^6
				5 sec	0.24	.0021	24.0	14.8	6.2×10^6
				15–120 min	0.06	.0016	16.6	9.8	4.3×10^6
				day	0.024	.0014	12.8	7.6	3.3×10^6
200	3.13	7.2	18.0	0.5 sec	7.0	.0030	39.3	23.2	2.2×10^7
				5 sec	2.4	.0028	28.1	16.8	1.6×10^7
				15–120 min	0.6	.0025	18.5	10.9	1.1×10^7
				day	0.24	.0023	14.0	8.3	0.8×10^7
2,000	31.3	15.5	90.0	0.5 sec	70.0	.0026	52.0	30.8	6.2×10^7
				5 sec	24.0	.0028	35.4	21.0	4.2×10^7
				15–120 min	6.0	.0029	22.0	13.0	2.6×10^7
				day	2.4	.0030	16.0	9.5	1.9×10^7
20,000	313	33.4	386.0	0.5 sec	700.0	.0023	71.6	42.4	1.8×10^8
				5 sec	240.0	.0024	49.4	29.2	1.3×10^8
				15–120 min	60.0	.0024	31.1	18.4	8.0×10^7
				day	24.0	.0026	22.4	13.3	5.8×10^7
200,000	3,130	72.0	1,800.0	0.5 sec	7,000.0	.0019	95.0	56.2	5.2×10^8
				5 sec	2,400.0	.0021	67.0	39.6	3.7×10^8
				15–120 min	600.0	.0022	41.0	24.2	2.3×10^8
				day	240.0	.0023	30.0	17.7	1.7×10^8
Part B. Speed With Full Laminar Flow									
2	0.313	1.55	9.0	0.5 sec	0.07	.0016	12.6	7.45	1.6×10^6
				5 sec	0.024	.0017	9.2	5.44	1.1×10^6
				15–120 min	0.006	.0022	5.2	3.07	6.2×10^5
				day	0.0024	.0027	3.6	2.13	4.3×10^5
20	0.313	3.34	3.86	0.5 sec	0.7	.00070	49.6	29.4	1.3×10^7
				5 sec	0.24	.00080	32.7	19.4	8.4×10^6
				15–120 min	0.06	.00090	19.6	11.6	5.1×10^6
				day	0.024	.0010	14.2	8.4	3.7×10^6
200	3.13	7.2	18.0	0.5 sec	7.0	.00045	74.0	43.8	4.1×10^7
				5 sec	2.4	.00052	47.1	27.8	2.6×10^7
				15–120 min	0.6	.00065	28.8	17.0	1.6×10^7
				day	0.24	.00070	20.8	12.3	1.2×10^7
2,000	31.3	15.5	90.0	0.5 sec	70.0	.00025	113.2	67.1	1.4×10^8
				5 sec	24.0	.00030	74.6	44.1	8.9×10^7
				15–120 min	6.0	.00035	44.5	26.3	5.3×10^7
				day	2.4	.00041	31.3	18.5	3.7×10^7
20,000	313	33.4	386.0	0.5 sec	700.0	....	......	......	....
				5 sec	240.0	....	......	......	....
				15–120 min	60.0	.00021	70.3	41.6	1.8×10^8
				day	24.0	0.00025	48.8	28.9	1.3×10^8

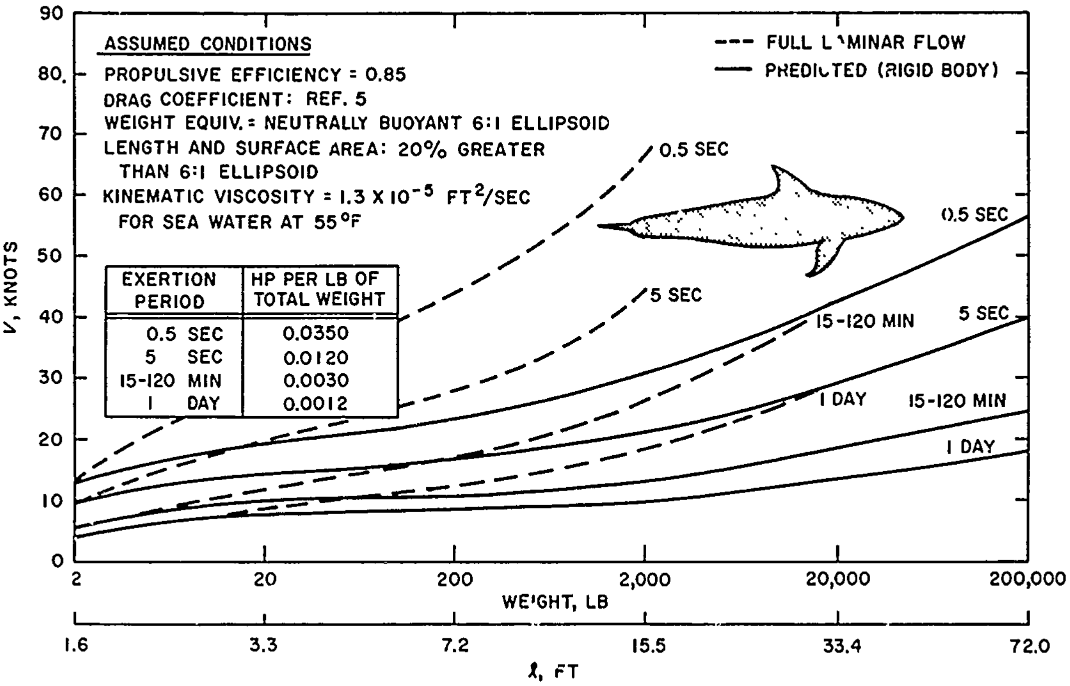


FIG. 24. Estimated Speed of Cetaceans, Using Rigid Body Drag and Human Power Ratios.

COMPARISON WITH OBSERVATIONS

It is interesting to first compare the sightings reported by Johannessen and Harder in Ref. 1 with the predicted values. The sightings showed maximum porpoise speeds of 17 to 18 knots for periods of 8 to 25 minutes. These porpoises being Pacific Whitesided Dolphins, their typical weight is 200 pounds. Figure 24 shows that the expected top speed is only 11 knots and the laminar speed is 17 to 18 knots. Therefore, it may be concluded that either their power is unusually high or their boundary layer is fully laminar and not chiefly turbulent, as expected for a value of $R\ell = 1.5 \times 10^7$. This performance deviates from the expected by a factor of four.

It is also noted in Ref. 1 that porpoise speeds of 19.6 to 21 knots were observed for 1 to 2 minutes, suggesting that sustained travel at this speed was beyond those porpoises' ability. Assuming that the power ratios of humans are applicable, this result again agrees with the estimates of Fig. 24, if the boundary layer is fully laminar at $R\ell = 2 \times 10^7$.

A killer whale, between 15 and 24 feet long, was reported in Ref. 1 to have approached a ship at about 30 knots and then to have swum around it for 20 minutes at a speed in excess of the ship speed of 20.6 knots. Figure 24 shows that the expected speed for periods between 15 minutes and 2 hours is about 16 knots and the laminar speed is about 35 knots. These results indicate either about 50% laminar flow or else about five times the expected power. The laminar flow would extend to a Reynolds number of 3 to 4×10^7, which is quite possible using some type of boundary layer control.

A sighting by W. Von Winkle, also reported in Ref. 1, states that a school of blackfish (a type of whale) circled for several days a Navy vessel traveling at 22 knots. These cetaceans were between 12 and 15 feet long. In this case, the daily expected speed is 9 to 10 knots and the daily

laminar speed is between 16 and 18 knots. For a 2-hour period, the laminar speed would be 24 knots. This sighting indicates that the whales probably not only had full laminar flow but that their endurance for a daily period approaches human endurance for a period of 2 to 4 hours—the power ratio being about 2:1. The Reynolds number for full laminar flow is 4×10^7. If the boundary layer was not laminar, which is highly improbable, the power required would be another factor of eight.

The performance reported by Gray in Ref. 2 of a 200-pound porpoise swimming at 20 knots for at least 7 seconds is seen in Fig. 24 to lie between the expected value of 15 knots and the laminar value of 26 knots. The 15-minute expected value is 11 knots and the 15-minute laminar value is 17 knots. This sighting is therefore explainable by laminar flow in the region of $R_\ell = 2 \times 10^7$.

An interesting observation of a blue whale that traveled at 20 knots for 10 minutes and at 14.5 knots for 2 hours is reported by Gawn in Ref. 6. Since a blue whale can weigh as much as 200,000 pounds, this performance produced somewhat less than the predicted values of 24 knots for 15 minutes and 18 knots for an all-day period. This sighting is fully explainable on the basis of turbulent flow and human power ratios.

PORPOISE JUMP

An interesting observation of a different type is the porpoise jump reported by Gero in Ref. 3. A graph on page 18 of Ref. 3 of (acceleration) thrust versus time depicts the performance of a porpoise that weighed 400 pounds and that jumped 7 feet above the water from a motionless underwater position. The acceleration took place in 0.6 to 0.7 second. By applying the standard thrust, momentum, power, and energy relationships, presented earlier in this report, the exit velocity is seen to be 12.5 knots and the horsepower output to be 0.021 hp/lb of total weight. This value of power output, making further allowance for propulsive efficiency, is comparable to the 0.035 hp/lb of humans for a 0.5-second period. In this example, the drag is not of great significance in view of the relatively low top speed. This result further shows that the power output of cetaceans is not unusual.

FISH

The largest power output of a fish that was measured and recorded by Gero (Ref. 3) was for the barracuda (his number 24) weighing 20 pounds, which was seen to produce 0.040 hp/lb and a top speed of 23.5 knots. The expected speed for this power is 20 knots and the laminar speed is 30 knots. Unfortunately, the exertion period is not mentioned. However, with the reported thrust measurements, it would require about 1 second to accelerate 20 pounds to this top speed, making due allowance for frictional drag. Although this power output is slightly greater than expected for the period, it may be explained by the extreme exertion that occurred in this single case during a period of unusual stress. Similar phenomena have been observed in humans, in cases of unusual stress. The hydrodynamic results indicate over 50%, but not complete, laminar flow. It is entirely possible that full laminar flow would normally exist, except that the fishline Gero used in his piscatometer, a device used for the determination of thrust, velocity, and horsepower of large salt-water fish, contacted one side of the barracuda's body. This could well cause at least one-third of the boundary layer to become turbulent, even if it would otherwise be entirely laminar. This is one possible shortcoming of the piscatometer, even though it is a good method of measuring power.

BOW-WAVE RIDING

Another, and final, illustration of porpoise performance is the result of an experimental study reported by Perry, Acosta, and Kiceniuk in Ref. 7. These investigators placed a rigid streamlined model in a simulated ship bow-wave formed in the Free Surface Water Tunnel at the California Institute of Technology. By inclining the submerged (finless) body parallel to the water surface, just ahead of the wave crest, they showed that the resulting pressure distribution on the body produced a thrust that was adequate to overcome its hydrodynamic drag. Their conclusion states that this tends to verify the contention of Hayes that porpoises can ride motionless, without exertion, in the bow-wave of ships because of the resulting pressure distribution around their bodies. It is therefore seen that the reported cetacean speeds are only valid in determining performance when cetaceans swim at some distance from ships.

FURTHER ANALYSIS OF FIG. 24

It is interesting to study Fig. 24 in view of these results. It is known that blue whales weigh as much as 200,000 pounds. Figure 24 shows that in fully turbulent flow the blue whale might travel at 18 knots for 1 day, at 24 knots for 2 hours, at 40 knots for 5 seconds, or at 56 knots for 0.5 second. It is readily apparent that, being of such large bulk, it could not accelerate its mass to reach top speed in 0.5 second or even in 5 seconds. However, it can reach speeds, according to this analysis, of 25 and possibly 30 knots. For the same period, this speed exceeds that obtainable by any sea animal weighing up to 1,200 pounds with pure laminar flow. For an all-day period, a blue whale might travel as fast as any other animal weighing up to 1,600 pounds with pure laminar flow. The blue whale, in fact, with turbulent flow, can travel all day at a speed about equal to that sustained for 15 minutes by a 200-pound porpoise with full laminar flow. This calculation pertains only to smooth bodies and would not apply to barnacle-encrusted whales.

LOW-DRAG HYPOTHESES

A number of hypotheses have been proposed that may explain the existence of low drag.

Perhaps the most reasonable hypothesis is the one on surface damping presented by Kramer in Ref. 8, 9, and 10. In Ref. 9 Kramer obtained 1.6 feet of laminar flow on a 4-foot model at a model Reynolds number of 1.5×10^7. This indicates a laminar-flow Reynolds number of 6×10^6, even with the presence of a nose section and a slight adverse pressure gradient. The model was covered with a special fluid-backed resilient rubber coating. The hypothesis is that tiny disturbances in laminar flow, which normally build up to cause turbulence, are damped out by the resilient coating, thereby maintaining laminar flow. This coated model had only 40% of the drag of an uncoated rigid model. Although further development is needed to make this coating more practical for bodies traveling at Reynolds numbers of 4×10^7 and above, it may well be the explanation for low drag in sea animals.

Another possibility for reducing drag by maintaining laminar flow is that of shape modification, presented by Schlichting in Ref. 11. By maintaining a favorable (reducing) pressure gradient to perhaps the midpoint of a streamlined body, or beyond, a greater length of laminar flow is obtained. This result is reflected in the graph on page 6-16 of Ref. 5, which shows that the laminar length on a body may extend to about 2 to 3×10^6. This effect is limited since the amount of laminar flow retained beyond $R_\ell = 2 \times 10^7$ is insignificant.

Another interesting method of extending the laminar region is by changing the temperature in the boundary layer. This method is discussed in chapter 17 of Ref. 11. The object is to reduce the viscosity of the inner region of the boundary layer in such a way as to modify the boundary layer profile into a shape that makes it more stable, thereby tending to keep it laminar. The ef-

fect of temperature change on viscosity alone is insignificant compared with this stabilizing effect. In air the desired result is accomplished by reducing viscosity by cooling; whereas in water it is done by heating. The effectiveness of this method, however, is believed limited by the turbulence introduced by convection currents.

Two other methods of possibly reducing drag depend upon body undulations. One method suggests the extension of laminar flow by means of an unsteady velocity, or pressure gradient. This method is discussed in chapter 11 of Ref. 11. The second method is presented by Rosen in Ref. 12. This method involves the formation of a vortex near the nose of a body and its resulting effect on the body.

Although drag reduction is not involved, a very complete analysis of the thrust and corresponding power required for propelling a two-dimensional body by undulation is presented by Wu (Ref. 13) and Kelly (Ref. 14).

It is conceivable that various forms of fish and cetaceans may use different methods of reducing drag, different combinations of methods, or no methods at all. Methods other than those presented might even present the correct explanation.

SUMMARY

Assuming that the reported observations of cetaceans and fish are valid, unusual performance exists. The best correlations between theory and observation suggest that this is due primarily to low drag and perhaps secondarily to high power. The reduction in drag appears to be equivalent to that obtained by extending the laminar boundary layer of a flat plate by a factor of 10. This extension is equivalent to a transition Reynolds number of around 4×10^7. The power output of sea animals is in general equal to, but in some cases may range up to twice as much as, that of human beings of equivalent body weight. It is extremely important to include the exertion period in any measurements of power, since the known power output of an animal can vary by a factor of 30, depending on the exertion time.

CONCLUSIONS AND RECOMMENDATIONS

The results of the porpoise studies at Convair and the analysis of the open-ocean sightings provide the following conclusions and recommendations:

1. The results of the performance tests of Notty show no unusual physiological or hydrodynamic phenomena.

2. During a total of 35 runs by Notty, without a collar, the top speed was only 25.1 ft/sec, or about 15 knots.

3. Results of the glide tests showed that the drag of the porpoise is essentially the same as that of an identical inanimate body. The drag measurements indicated that turbulence begins at a distance from the nose of about 20% of the porpoise's length.

4. The effective drag of the porpoise while swimming appears in these tests to be essentially the same as while gliding.

5. The maximum power recorded from acceleration or drag runs was 2.1 hp for 0.5 second and 1.5 hp for 6 seconds. These values are comparable to human power levels.

6. A variation in water depth from 4.5 to 6.0 feet had no noticeable effect on top speed or drag.

7. Except for slightly higher power levels recorded on the first run of each day, no major difference in performance was observed in consecutive runs, in general, as long as the porpoise was allowed to rest 30 minutes or longer between runs.

8. Photographs of body and tail movement indicate that thrust is probably developed by both the tail and the body. Significant body undulation occurs during swimming.

9. Analysis of sea-animal performance reported in the available references indicates that the drag of many sea animals is significantly lower than the expected value. Some evidence exists of higher power output than that of humans, but not of the magnitude that appears in the drag analysis. It is possible that the relatively low performance of Notty in these tests was due to one or more of the following: water turbulence, water contamination, psychological factors, inadequate training, limited tank length, long confinement, shallow water, or unknown factors.

It is recommended that further tests of top speed be conducted under more normal open-ocean conditions in order to check the results of this report. Many of the experimental methods and theoretical analyses introduced in this report will be of use in such future studies.

Appendix A
DRAG ANALYSIS OF THE PORPOISE NOTTY

by

J. A. Poore[1]

The dimensions used in this report are those of the porpoise known as Notty. The equations used to determine the drag can be found in Ref. 5.

The drag of the porpoise was determined for three different flow cases: completely laminar, completely turbulent, and the occurrence of transition at the point of maximum body thickness (0.4ℓ). The drag in each flow case was determined for forward velocities of 10, 20, and 30 ft/sec. No attempt was made to calculate any interference drag, since it is believed the porpoise has developed optimum fairings for his appendages. Roughness drag caused by the eyes and mouth was estimated to be 3% of the skin friction drag.

The wetted area was calculated by assuming the porpoise had a circular cross section. The projected areas of the tail, dorsal fin, and flippers were determined from equivalent triangles that closely approximate the actual sizes of these appendages.

The equations used to calculate the laminer flow drag of the body are

$$C_f = 1.328/\sqrt{R_\ell}$$
$$C_D = C_f[1 + 1.5(d/\ell)^{1.5} + 7(d/\ell)^3]$$

and for the appendages

$$C_f = 1.328/R_c^{1/2}$$
$$C_D = 2C_f[1 + 2t' + 60(t')^4]$$

The equations used to calculate turbulent flow drag of the body are

$$\log(R_\ell C_f) = 0.242/C_f^{1/2}$$
$$C_D = C_f[1 + 1.5(d/\ell)^{1.5} + 7(d/\ell)^3]$$

and for the appendages

$$C_f = 0.074/R_c^{1/5}$$
$$C_D = 2C_f[1 + 2t' + 60(t')^4]$$

In calculating the drag of the body, with transition occurring at the point of maximum body diameter (0.4ℓ), it was assumed the momentum thickness at this point was the same for laminar and turbulent flow. This gave an equivalent length of the turbulent region, allowing the skin friction drag coefficient to be more accurately determined. The drag values of the appendages for this flow case were taken from Fig. 6-2 of Ref. 5.

The thickness-to-chord ratio of the appendages was assumed to have a value of 0.1. The body fineness ratio, d/ℓ, was 0.18. The results of this analysis are given in Tables 3, 4, and 5.

[1] The author wishes to acknowledge the help of T. G. Lang in outlining the studies that are Appendixes A, B, and C of this report, and in checking their results.

TABLE 3. ELEMENTS OF PORPOISE DRAG, ASSUMING COMPLETELY LAMINAR FLOW

Item	Drag data		
	V = 10 ft/sec	V = 20 ft/sec	V = 30 ft/sec
Body			
R	6.1×10^6	1.22×10^7	1.83×10^7
C_f	0.000538	0.000380	0.000310
C_{D_w}	0.000622	0.000439	0.000358
S_w, ft^2	15.59	15.59	15.59
$D/q = C_D S$, ft^2	0.0097	0.0068	0.0056
Roughness drag coef., C_{D_r}	0.000016	0.000011	0.000009
Roughness drag area, $(D/q)_r$, ft^2	0.0003	0.0002	0.0001
Total body D/q, ft^2	0.0100	0.0070	0.0057
Dorsal fin			
R_c	5.3×10^5	1.06×10^6	1.59×10^6
C_f	0.00182	0.00129	0.00105
C_D	0.00439	0.00311	0.00253
S, ft^2	0.273	0.273	0.273
D/q, ft^2	0.0012	0.0008	0.0007
Flippers			
R_c	2.78×10^5	5.56×10^5	8.34×10^5
C_f	0.00252	0.00178	0.00145
C_D	0.00608	0.00429	0.00350
S, ft^2	0.413	0.413	0.413
D/q, ft^2	0.0025	0.0018	0.0014
Tail			
R_c	3.79×10^5	7.58×10^5	1.14×10^6
C_f	0.00216	0.00153	0.00124
C_D	0.00521	0.00369	0.00300
S, ft^2	0.527	0.527	0.527
D/q, ft^2	0.0027	0.0019	0.0016
Total			
Total drag area, ft^2	0.0164	0.0115	0.0094
Dynamic pressure, q, lb/ft^2	99.5	398.0	895.5
Drag, lb	1.63	4.58	8.42

TABLE 4. ELEMENTS OF PORPOISE DRAG, ASSUMING COMPLETELY TURBULENT FLOW

Item	Drag data		
	V = 10 ft/sec	V = 20 ft/sec	V = 30 ft/sec
Body			
R_ℓ	6.1×10^6	1.22×10^7	1.83×10^7
C_f	0.00318	0.00284	0.00266
C_{D_w}	0.00367	0.00328	0.00308
S_w, ft^2	15.59	15.59	15.59
D/q, ft^2	0.0572	0.0511	0.0480
C_{D_r}	0.000095	0.000085	0.000080
$(D/q)_r$, ft^2	0.0015	0.0013	0.0012
Total body drag area, ft^2	0.0587	0.0524	0.0492
Dorsal fin			
R_c	5.3×10^5	1.06×10^6	1.59×10^6
C_f	0.00530	0.00462	0.00425
C_D	0.01280	0.0111	0.0102
S, ft^2	0.273	0.273	0.273
D/q, ft^2	0.0035	0.0030	0.0028
Flippers			
R_c	2.78×10^5	5.56×10^5	8.34×10^5
C_f	0.00604	0.00525	0.00484
C_D	0.0146	0.0127	0.0117
S, ft^2	0.413	0.413	0.413
D/q, ft^2	0.0060	0.0052	0.0048
Tail			
R_c	3.79×10^5	7.58×10^5	1.14×10^6
C_f	0.00566	0.00493	0.00455
C_D	0.0137	0.0119	0.0110
S, ft^2	0.527	0.527	0.527
D/q, ft^2	0.0072	0.0063	0.0058
Total D/q, ft^2	0.0754	0.0669	0.0626
q, lb/ft^2	99.5	398.0	895.5
Drag, lb	7.50	26.63	56.06

TABLE 5. ELEMENTS OF PORPOISE DRAG, ASSUMING TRANSITION AT MAXIMUM BODY THICKNESS (0.4ℓ)

Item	Drag data		
	V = 10 ft/sec	V = 20 ft/sec	V = 30 ft/sec
Body			
A. Laminar Region			
R_ℓ	2.46×10^6	4.92×10^6	7.39×10^6
C_f	0.000846	0.000599	0.000489
C_{D_w}	0.000977	0.000691	0.000565
S_w, ft^2	6.76	6.76	6.76
D/q, ft^2	0.0066	0.0047	0.0038
C_{D_r}	0.000025	0.000018	0.000015
$(D/q)_r$, ft^2	0.0002	0.0001	0.0001
Total laminar D/q, ft^2	0.0068	0.0048	0.0039
B. Turbulent Region			
Laminar boundary layer thickness at 0.4ℓ, δ, ft	0.00947	0.00671	0.00547
Momentum thickness, Θ_ℓ, ft ($\Theta = 0.12\delta$)	0.00114	0.000805	0.000656
Equivalent turbulent boundary layer thickness, δ_{turb}, ft ($\delta_t = 10.3\Theta$)	0.01169	0.00828	0.00675
Equivalent turbulent region length, ft	4.486	4.365	4.308
R_c	4.08×10^6	7.94×10^6	1.175×10^7
C_f	0.00341	0.00305	0.00286
C_{D_w}	0.00394	0.00352	0.00330
S_w, ft^2	8.83	8.83	8.83
D/q, ft^2	0.0348	0.0311	0.0291
Total body D/q, ft^2	0.0416	0.0359	0.0330
Dorsal fin			
R_c	5.3×10^5	1.06×10^6	1.59×10^6
C_D	0.0062	0.0053	0.0050
S, ft^2	0.273	0.273	0.273
D/q, ft^2	0.0017	0.0014	0.0014
Flippers			
R_c	2.78×10^5	5.56×10^5	8.34×10^5
C_D	0.0070	0.0061	0.0055
S, ft^2	0.413	0.413	0.413
D/q, ft^2	0.0029	0.0025	0.0023
Tail			
R_c	3.79×10^5	7.58×10^5	1.14×10^6
C_D	0.0065	0.0056	0.0053
S, ft^2	0.527	0.527	0.527
D/q, ft^2	0.0034	0.0030	0.0028
Total D/q, ft^2	0.0496	0.0428	0.0395
q, lb/ft^2	99.5	398.0	895.5
Drag, lb	4.93	17.03	35.37

Appendix B
DRAG OF A PORPOISE WITH COLLAR

by

J. A. Poore

Calculating the drag of a porpoise with an attached collar is a relatively difficult task, since the literature is lacking on the drag of a collar on a body or of a transverse circular cylinder on a wall.

The method used to calculate the drag area is dependent on collar drag coefficient. Only the drag coefficient for the 1/16-inch collar was found in the literature (Ref. 15). The remaining drag coefficients are estimated using approximate methods. The method used to determine the drag areas follows. Summaries of results are given at the close of each section.

The flow ahead of the collar is assumed to be laminar. The equations for laminar-flow drag are taken from Ref. 5. The Reynolds number for the laminar region is

$$R_x = 1.36 \times 10^5 V$$

The skin friction drag coefficient is given by

$$C_f = 1.328/R_x^{1/2}$$

or

$$C_f = 0.0036/V^{1/2}$$

The results, with no over-velocity correction, are

V, ft/sec	C_f
10	0.00114
20	0.000805
30	0.000657

At the transition point, the momentum thickness of the turbulent region is equal to that of the laminar region plus that caused by the collar:

$$\Theta_t = \Theta_\ell + \Theta_c$$

The laminar momentum thickness is

$$\Theta_\ell = 0.12\delta_\ell$$

where δ_ℓ is the thickness of the boundary layer at the collar and is determined by

$$\delta_\ell = 5.5x/R_x^{1/2}$$

For the laminar region, the momentum thicknesses are

V, ft/sec	Θ_ℓ, ft
10	0.00085
20	0.00060
30	0.00049

The momentum thickness of the collar is given by

$$\Theta_c = 0.5C_D.f$$

where

f = collar tube diameter, ft

$C_{D.}$ = collar drag coefficient based on frontal area

The collar drag coefficient is obtained from the equation

$$C_{D.} = [(f - \delta_{\Delta})/f]C_{D_o}$$

where δ_{Δ} is the displacement thickness of the boundary layer at the collar and C_{D_o} is 53% of the drag coefficient of a two-dimensional circular cylinder in the free flow. This value is

$$C_{D_o} = 0.82$$

The equation for collar momentum thickness becomes

$$\Theta_c = 0.41(f - \delta_{\Delta})$$

A summary of the collar momentum thicknesses ($\Theta_c/100$) follows:

	Collar tube diameter, in.						
V, *ft/sec*	*1*	*3/4*	*1/2*	*1/4*	*3/16*	*1/8*	*1/16*
10	3.32	2.47	1.62	0.762	0.549	0.336	0.122
20	3.35	2.50	1.64	0.786	0.574	0.361	0.145
30	3.36	2.51	1.66	0.799	0.586	0.373	0.161

The momentum thicknesses of the laminar region plus collar ($\Theta_{\ell+c}/100$) are summarized in the following table:

	Collar tube diameter, in.						
V, *ft/sec*	*1*	*3/4*	*1/2*	*1/4*	*3/16*	*1/8*	*1/16*
10	3.40	2.55	1.70	0.847	0.634	0.421	0.207
20	3.41	2.56	1.70	0.846	0.634	0.421	0.205
30	3.41	2.56	1.71	0.848	0.635	0.422	0.210

The momentum thickness at the beginning of the turbulent region is equated to the above to find the equivalent length of turbulent flow caused by the laminar region plus collar. Using the additional length of the turbulent area, the Reynolds number at the transition point is obtained. This parameter is determined by the equation

$$R_{\Delta x} = 815 \times 10^5(\Theta_t V)^{7/6}$$

The values obtained for $R_{\Delta x} \times 10^6$ are tabulated below:

	Collar tube diameter, in.						
V, *ft/sec*	*1*	*3/4*	*1/2*	*1/4*	*3/16*	*1/8*	*1/16*
10	23.2	16.5	10.32	4.57	3.26	2.02	0.884
20	56.0	37.2	23.2	10.25	7.37	4.54	1.96
30	83.6	59.4	37.4	16.54	11.79	7.31	3.24

The Reynolds number at the end of the turbulent region is determined from the equation

$$R_e = 4.74 \times 10^5 V + R_{\Delta x}$$

The values for $R_e \times 10^6$ are given in the following table:

	Collar tube diameter, in.						
V, *ft/sec*	*1*	*3/4*	*1/2*	*1/4*	*3/16*	*1/8*	*1/16*
10	27.9	21.2	15.06	9.31	8.00	6.76	5.62
20	65.5	46.7	32.7	19.73	16.85	14.02	11.44
30	97.8	73.6	51.6	30.7	26.0	21.5	17.46

The skin friction drag coefficient for the turbulent region is found from the equation

$$C_T = dC_f/d(R_x/R_l)$$

where C_T is the local drag coefficient and is determined by the equation

$$C_T = 0.37/(\log R)^{2.58}$$

The above equation, taken from Ref. 5, is presented here graphically as Fig. 25. A graphic integration of Fig. 25 will give the average skin friction coefficient. The results of this integration ($C_f \times 10^3$) are given below:

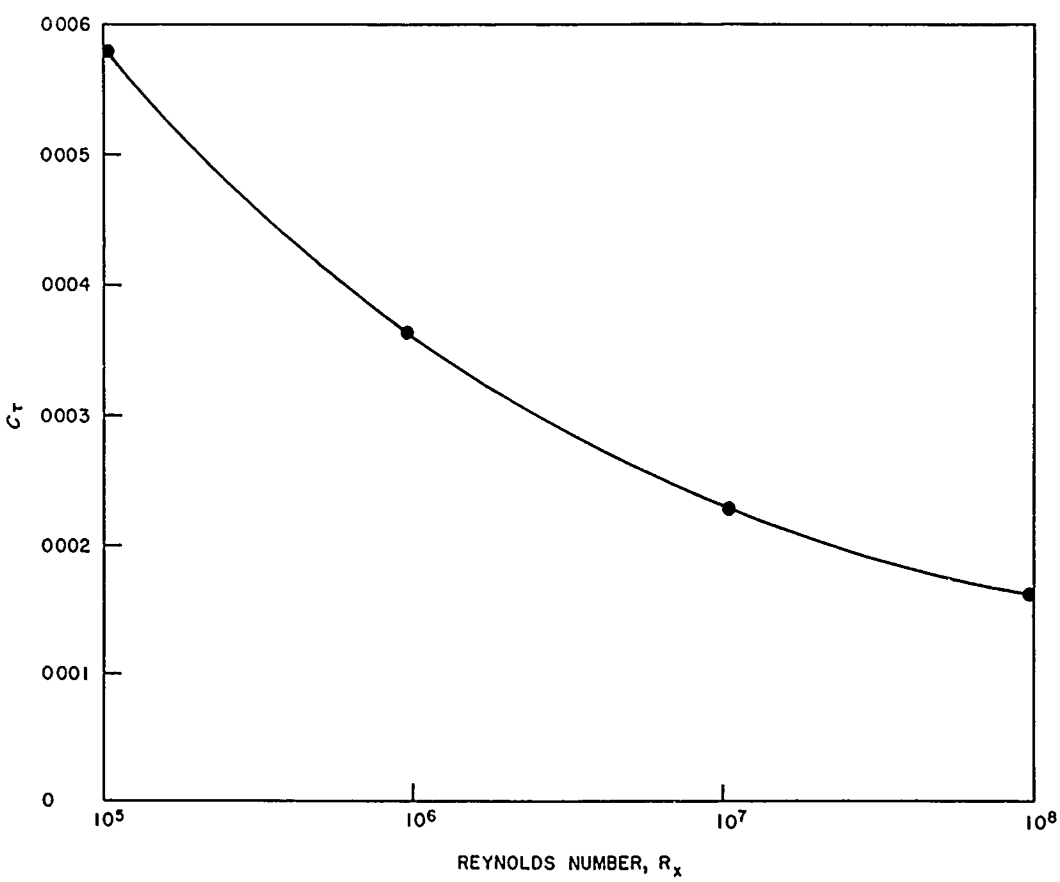


FIG. 25. Local Drag Coefficient Versus Reynolds Number.

V, *ft/sec*	Collar tube diameter, in. 1	3/4	1/2	1/4	3/16	1/8	1/16
10	2.15	2.25	2.37	2.58	2.68	2.82	3.08
20	1.85	1.97	2.12	2.33	2.40	2.50	2.66
30	1.75	1.82	1.95	2.18	2.25	2.35	2.48

The frictional drag coefficient of the porpoise, based on wetted area, is obtained by adding the skin friction coefficients of the laminar and turbulent regions and applying a correction factor of 1.15 for over-velocity effects. The frictional drag coefficient of the porpoise body ($C_{D_w} \times 10^3$) is tabulated below:

V, *ft/sec*	Collar tube diameter, in. 1	3/4	1/2	1/4	3/16	1/8	1/16
10	3.78	3.90	4.04	4.27	4.39	4.55	4.85
20	3.05	3.18	3.36	3.60	3.68	3.80	3.98
30	2.76	2.84	2.99	3.25	3.34	3.45	3.60

The drag area of the porpoise with an attached collar is obtained by summing the drag areas of the components. The formula is

$$D/q = C_{D_w} S_w + (D/q)_a + C_{D_c} S.$$

where

$(D/q)_a$ = drag area of the appendages, ft^2

S_w = porpoise body, wetted area, ft^2

$S.$ = collar frontal area, ft^2

C_{D_c} = collar drag coefficient based on body wetted area

C_{D_w} = frictional drag coefficient of porpoise body based on body wetted area

The total drag area of the porpoise with attached collar, in ft^2, is tabulated below:

V, *ft/sec*	Collar tube diameter, in. 1	3/4	1/2	1/4	3/16	1/8	1/16
10	0.267	0.215	0.164	0.118	0.107	0.097	0.090
20	0.256	0.203	0.154	0.107	0.096	0.086	0.077
30	0.252	0.199	0.150	0.102	0.091	0.081	0.071

As an aid in comparing the theoretical values with the experimental, the above values are plotted and presented in Fig. 26.

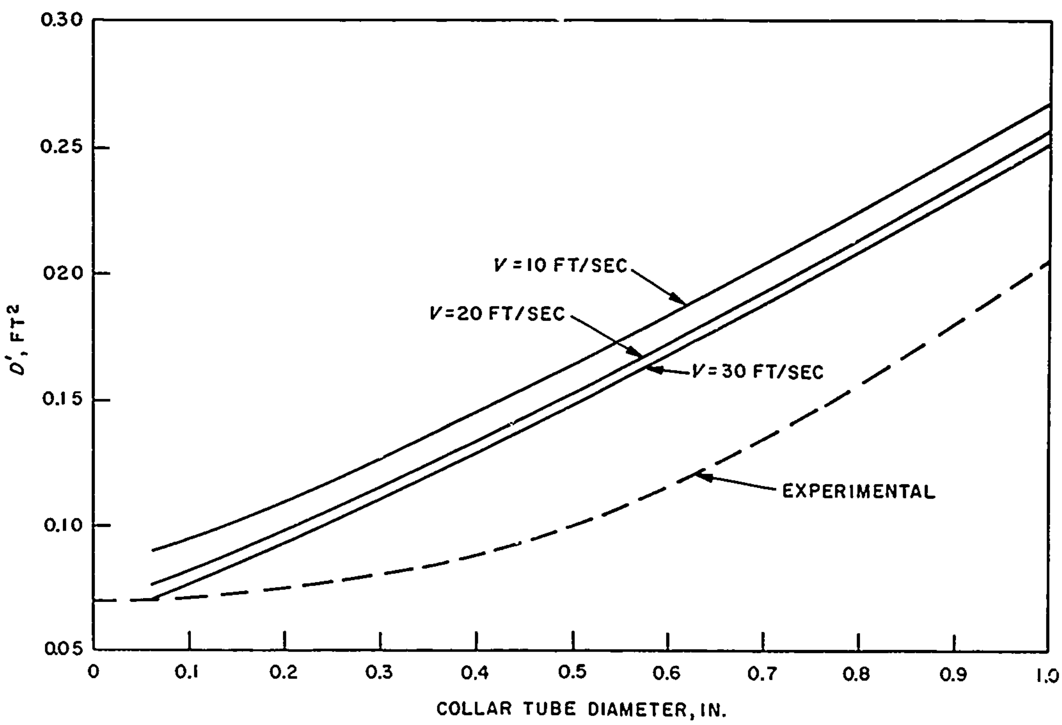


FIG. 26. Comparison of Experimental and Theoretical Drag Area of Porpoise With Collar.

Appendix C
WAVE DRAG OF THE PORPOISE NOTTY

by

J. A. Poore

In this investigation, the porpoise was considered to be a rigid body with a fineness ratio of 5.55. All information used to determine the wave drag was obtained from Fig. 11-18, Ref. 5. This graph was enlarged and is reproduced here as Fig. 27.

A literature search was conducted for the purpose of finding a working formula to account for any effect of tank walls and bottom on wave resistance. Nothing suitable was found. It was assumed that the tank walls, because of their large spacing relative to the porpoise's dimensions, have no effect on wave resistance. The tank bottom theoretically reduces wave drag. Therefore,

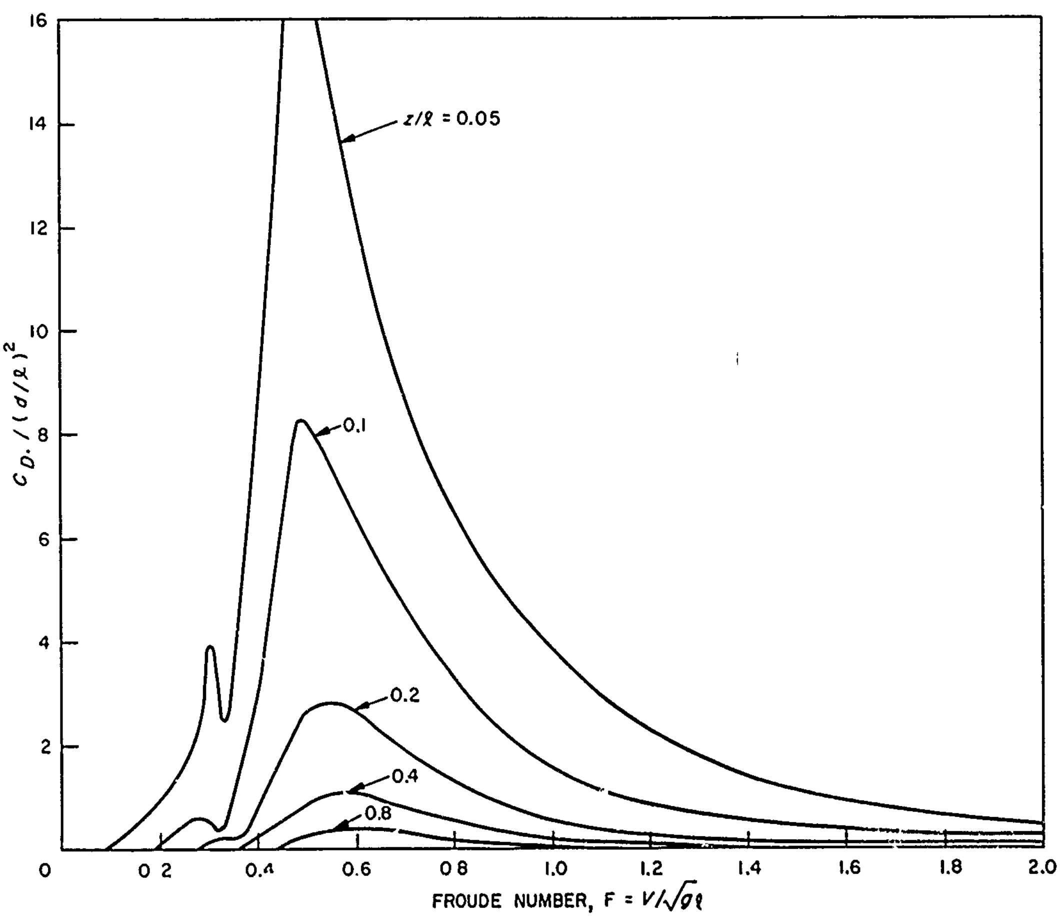


FIG. 27. Theoretical Wave Drag Versus Velocity, for Varying Submergence Ratios.

to allow no correction for this effect will give conservative results. The problem, as treated herein, is one of finding the wave drag of the porpoise in an unbounded fluid for varying depths of immersion.

It is interesting to note the rapidity with which the wave resistance decreases with increasing depth. Below a depth of 2 body diameters the wave drag is essentially zero for velocities of 20 and 30 ft/sec. Since the tank has a maximum water depth of 6 feet, it is seen from the results that the 10-ft/sec case will have a wave drag at any depth in the tank.

The explanation for the decrease in wave drag due to increased depth is fairly simple. As the depth increases, the amplitude of the disturbed surface wave decreases. Eventually a depth will be reached where the amplitude of the disturbed wave is negligible. Since wave drag is a function of the surface wave, it can be considered negligible when the wave amplitude is negligible.

The decrease in wave resistance caused by increased velocity has a more complicated explanation. Reference 16 gives the following reason: The crests of the bow-wave alternately reinforce and dampen those of the stern- and shoulder-wave systems. This reinforcing and damping effect accounts for the peaks and hollows in any curve of wave drag plotted against speed. As the velocity increases, the wave length increases. After a certain velocity is reached, the second wave of the bow system will fall astern of the ship and no further reinforcing of the shoulder and stern systems will occur. Above this speed, wave resistance will decline as the velocity increases.

The results obtained from Fig. 27 were plotted and are presented here in Fig. 28 and 29. It is felt that the assumption that the tank walls have no effect on wave drag may be an error. Further investigation of this effect and that of the tank bottom should be pursued as time permits.

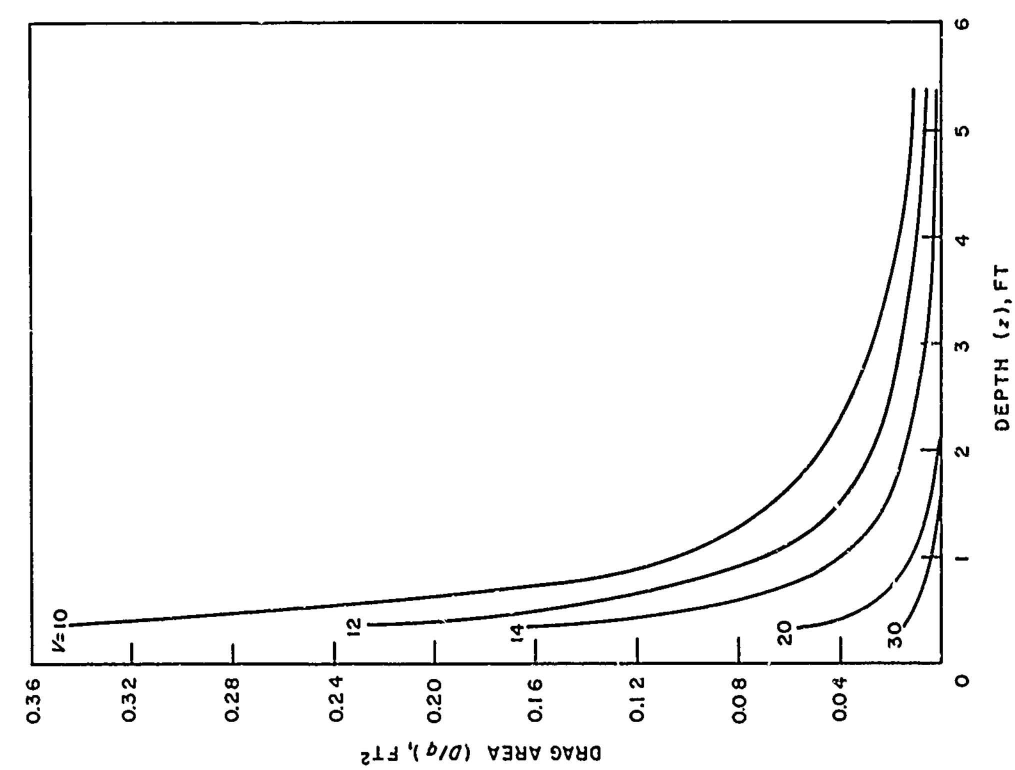


FIG. 28. Wave Drag Area Versus Depth, for Varying Velocity.

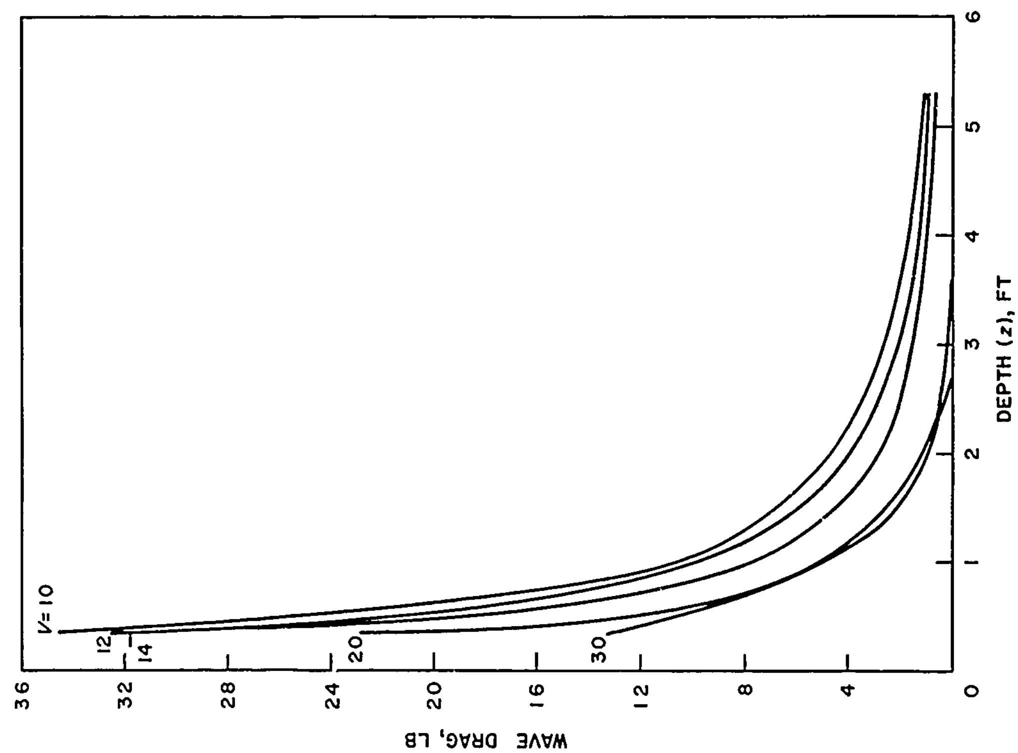


FIG. 29. Wave Drag Versus Depth, for Varying Velocity.

Appendix D
ANALYSIS OF DTMB TESTS OF COLLAR DRAG

Reference 17 presents drag data of a streamlined body with collars of various thicknesses. The body had a fineness ratio of 6, the collars were placed at a distance from the nose of 22.4% of the porpoise's length, and the tests were conducted at Reynolds numbers between 2.66×10^6 and 1.51×10^7. These conditions closely duplicate those of the porpoise at Convair. The purpose of these tests was to check both the calculated and experimental drag coefficients of the porpoise with and without collars.

Figure 30 shows the drag coefficient of the three collars tested at DTMB. The coefficients are plotted as a function of Reynolds number, and represent the difference in drag coefficient between the bare body and the body with a collar. Of prime significance is the fact that the drag coefficient based on collar projected area lies between 0.6 and 0.8. The trends of the curves are difficult to interpret since several factors are apparently interacting. Some of these factors are the following:

1. The critical Reynolds number of the collar itself can affect the collar drag.
2. The thickness of the body boundary layer relative to the thickness of the collar can change collar drag.
3. The thickening of the boundary layer behind the collar reduces body frictional drag.
4. The boundary layer thickenin· can sometimes increase the separation-drag occurring at the tail of the body.

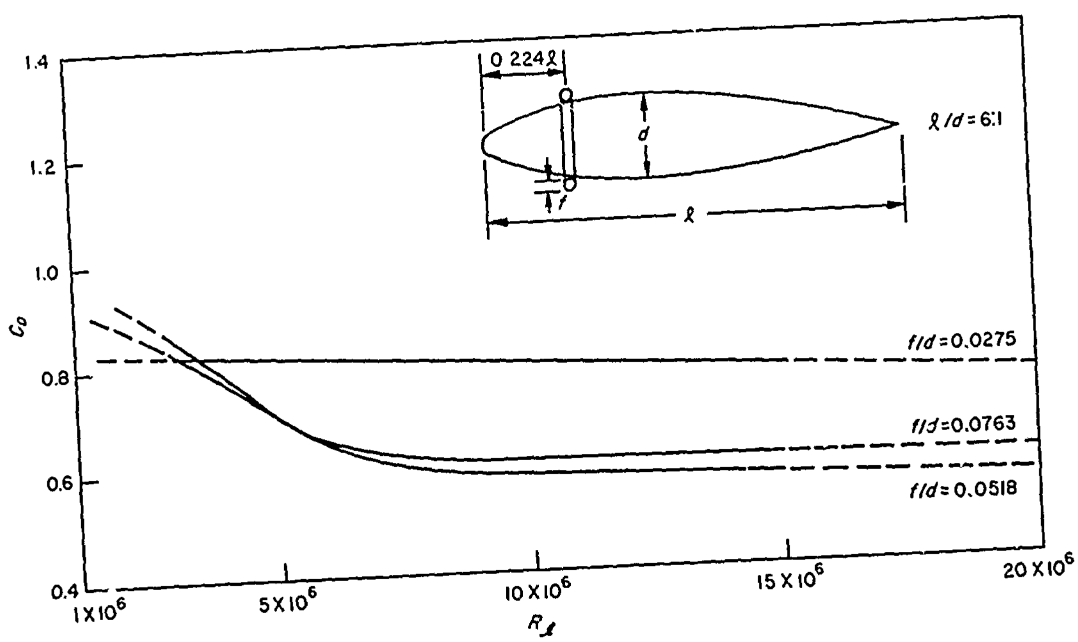


FIG. 30. Drag Coefficient of Collar Attached to Body.

TABLE 6. COMPARISON OF COLLAR DRAG COEFFICIENTS

Collar thickness, in.	Porpoise speed, ft/sec	$R_\ell \times 10^{-6}$	Collar drag coefficient			Max. porpoise speed, ft/sec	Max. collar drag,[a] lb	Porpoise drag horsepower	
			NOTS, calcd.	Porpoise, exptl.	DTMB, exptl.			Porpoise, exptl.	Modified by DTMB, exptl.[a]
1/4	12	6.3	0.87	......	0.81	......	......	......	......
1/2	11	5.8	0.82	0.26	0.72	13.9	16.2	0.49	0.78
3/4	10	5.2	0.81	0.40	0.68	13.2	19.6	0.60	0.82
1	9	4.7	0.80	0.54	0.75	12.9	25.6	0.80	1.00

[a] Based on C_D from DTMB tests.

Table 6 presents a comparison of the calculated collar drag coefficients, the experimental results on the porpoise at Convair, and the DTMB results. The results show that the calculated coefficients were higher than the DTMB results, but were in the same vicinity. Of prime importance, however, are the relatively low collar drag coefficients of the porpoise tests in contrast o the model results at DTMB. It is recalled that the experimental porpoise drag coefficients were used in estimating the drag horsepower of the porpoise with collars. From Table 6 it is seen that using the DTMB results, the porpoise drag horsepower values would increase from 0.49 to 0.78 hp with the 1/2-inch collar and from 0.80 to 1.00 hp with the 1-inch collar. This increase is justified if the porpoise was slightly propelling itself during the glide runs, as discussed in this report. It is not justified if the collar drag was reduced because of the collar sinking into the body. Whether justified or not, these horsepower values still do not approach the peak acceleration horsepower of 2.0. This discrepancy is likely due to the following:

1. The collar is forced back against the porpoise's body, causing discomfort. The porpoise's tolerance to the drag force would increase with the collar size. Such an increase is seen in Table 6.
2. The exertion time period is greater for the top-speed runs with collars than for the runs to obtain peak acceleration. The horsepower output reduces rapidly with exertion time.

In conclusion, it is believed that the porpoise drag horsepower values reported earlier in this report should be somewhat increased. However, too many unknowns exist to justify modifying the results. In either case, the conclusions of this study would remain essentially unchanged.

NEGATIVE NUMBERS OF ILLUSTRATIONS

Fig. 1, LHL-P 22535-12; Fig. 2–30, none.

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ABSTRACT. This report deals with a series of tests—consisting of measurements of top speed, horsepower output, and drag coefficient—made to determine how a porpoise's power compares with that of other mammals, and how its hydrodynamic characteristics compare with those of conventional man-made submerged bodies. Results of the tests indicated no unusual physiological or hydrodynamic phenomena; power

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2 University of California, Institute of Engineering Research, Berkeley
  J. Harder (1)
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  Prof. H. Rouse (1)
  Prof. L. Landweber (1)
1 University of Miami, Marine Laboratory, Miami
1 University of Minnesota, St. Anthony Falls Hydraulic Laboratory, Minneapolis
1 University of Washington, Seattle (Department of Oceanography)
1 University of Wisconsin, Mathematics Research Center, Madison (L. M. Milne-Thomson)
2 Woods Hole Oceanographic Institution, Woods Hole, Mass.
  R. H. Backus (1)